Retrofit of Dunhuang 10 MW molten salt plant with a high temperature supercritical CO₂ cycle

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From Shouhang: Qi Zhipeng, Chen Wenlong, Wang Xihua, Jing Chengtao
Interest $\text{SCO}_2$ cycle for CSP

**Increase**

- **Efficiency**: For $T$ above 550°C
- **Flexibility**: Reduced start up time

**Reduce**

- **Water resource**: No more steam
- **Complexity**: Low number of equipment
- **Equipment Size**: Small turboset

Direct swap with steam cycle

-10 to -25% on LCOE
Today’s vision on $\text{SCO}_2$ technology roadmap for CSP

**Up to 560°C - Quick implementation of $\text{SCO}_2$ cycle**
- Power block reduction
- Same efficiency
- No change of molten salt

**Up to 650°C – $\text{SCO}_2$ commercial potential**
- Significant efficiency gain
- Optimized salt
- New bladed receiver

**Up to 750°C – Long term CSP future of $\text{SCO}_2$ cycle**
- High efficiency gain
- Use of halide salt w or w/ intermediate HTF
- Use optimized bladed receiver
- Use internally insulated tank
  - Could also used particles receivers

**Scope of present project**

Demonstrate cycle technology
Assess equipment supply chain
Prepare commercial project in 3 years

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Example of light-trapping bladed receiver

Ho, C.K., 2017, Solar Energy
EDF & Shouhang partnership

Companies profiles and interest for SCO₂ cycles

International utilities company
with business on all power generation, transport and commercialization chains
Leader in the low carbon power generation
Strong commitment in innovation and renewable power generation

Chinese leading equipment supplier for energy transition
with business in dry cooling system, CSP, waste heat recovery and multi energy system
Leader in CSP technologies in China (investor and supplier, Owner of SunCan brand)
Striving to innovate in CSP to maintain its competitive advantage

Aims of partnership

3 years project

✓ Assess the potential of SCO₂ cycles for near future CSP plant
✓ Develop a retrofit solution of Shouhang plant
✓ Operate and evaluate the performance of the demo cycle

Project signature & kick off ceremony
Existing molten salt plant in Dunhuang

Overall plant design
✓ Solar field - 180,000 m² (1500 Heliostat of 116 m²)
✓ Tower receiver (138 m high)
✓ Solar salt storage – 15 h (5800 t of solar salt)
✓ Steam cycle – 10 MW
✓ Air condenser

Investment of 420 M RMB (≈63 M$)

70 % equipment supply by Shouhang

In operation since November 2016

Achieve 6 days 24h continuous operation in July 2018
Project key target and schedule

Project key boundary hypothesis

✓ No change on molten salt system
✓ Installation parallel to steam cycle
✓ 10 MW+ net power
✓ 500°C+ temperature
✓ Similarities with future SCO₂ cycle for CSP

Demonstration key target

✓ Test key equipment
  (15 MW+ turbine, 20 MW MS heater, 40 MW+ heat recup.)
✓ Test recompression loop & intercooled compression
✓ Test advanced inventory control system
✓ Test up to 620°C operation
✓ Test high T molten salt loop with electrical heating

Overall project key milestones

- May 2018: Project kick off
- Oct 2018: Conceptual study completed
- Dec 2018: Feasibility study completed
- Feb 2019: Investment decision
- Mar 2019: Start equipment manufacturing
- Sep 2019: First equipment delivered & tested
- Sep 2020: Demonstration commissioning
- Nov 2020: Demonstration test start up
Cycle selection and design – methodology 1/2

Boundary hypothesis

1. Flow of 80 kg/s of 560°C molten salt
2. Has to cool the molten salt around 290°C
3. Provision for lower salt T and higher return T
4. Minimal achievable CO₂ temperature: 35°C
5. Maximal practical pressure: 250 bar

Performance hypothesis at pre-design stage

1. Turbine efficiency: 85 %
2. Compressor efficiency: 80 %
3. Achievable pinch in heat exchanger: 10°C

Free parameter

1. Cycle architecture
2. Maximal CO₂ temperature
3. Minimal CO₂ pressure
4. CO₂ flowrate

Objective function to maximize

\[ \text{Cycle net power} \approx \text{salt heat use} \times \text{cycle efficiency} \]
Cycle selection and design – methodology 2/2

Optimization driven design with 2 approaches

1. "classic design" by simulation based on expertise
   learn and understood the design drivers
2. global optimization tool based on MINLP optimizer coupled with a cycle superstructure
   sure to not miss a good solution and explore out of the box ideas

Cycle superstructure used for global optimization
The two reference SCO$_2$ cycles

<table>
<thead>
<tr>
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<th>max. efficiency</th>
<th>max. power</th>
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<tbody>
<tr>
<td><strong>T$_{\text{max}}$</strong></td>
<td>550°C</td>
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<td><strong>P$_{\text{min}}$</strong></td>
<td>80 bar</td>
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<td><strong>$\eta$</strong></td>
<td>35.9 %</td>
<td>33.3 %</td>
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<td><strong>Exit salt T</strong></td>
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<tr>
<td><strong>Power</strong></td>
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<td>11.4 MW</td>
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<td><strong>Rel. cost</strong></td>
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<td>0.76</td>
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<td><strong>P$_{\text{min}}$</strong></td>
<td>85 bar</td>
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<tr>
<td><strong>$\eta$</strong></td>
<td>41.1 %</td>
<td>33.2 %</td>
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<td><strong>Exit salt T</strong></td>
<td>401°C</td>
<td>290°C</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>8.7 MW</td>
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<tr>
<td><strong>Rel. cost</strong></td>
<td>1.28</td>
<td>0.97</td>
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Interest of compression intercooling

Intercooled regenerative

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<th>Parameter</th>
<th>First Value</th>
<th>Second Value</th>
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<td>535°C</td>
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<td>P\text{min}</td>
<td>85 bar</td>
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<tr>
<td>η</td>
<td>33.3 %</td>
<td>34.7 %</td>
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<tr>
<td>Exit salt T</td>
<td>290°C</td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td>11.4 MW</td>
<td>11.9 MW</td>
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</table>

No further significant amelioration

Intercooled recompression

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<thead>
<tr>
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<tr>
<td>P\text{min}</td>
<td>90 bar</td>
<td>85 bar</td>
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<tr>
<td>η</td>
<td>33.2 %</td>
<td>34.7 %</td>
</tr>
<tr>
<td>Exit salt T</td>
<td>290°C</td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td>11.4 MW</td>
<td>11.9 MW</td>
</tr>
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</table>
Evaluation of CO₂ preheat scheme

**Low temp. CO₂ preheating**

- Tmax: 430°C → 500°C
- Pmin: 85 bar
- η: 34.7% → 35.9%
- Exit salt T: 290°C
- Power: 11.9 MW → 12.3 MW

**High temp. CO₂ preheating**

- Tmax: 430°C → 460°C
- Pmin: 85 bar
- η: 34.7% → 36.8%
- Exit salt T: 290°C
- Power: 11.9 MW → 12.6 MW

**Recompressed CO₂ preheating**

- Tmax: 430°C → 485°C
- Pmin: 85 bar
- η: 34.7% → 36.7%
- Exit salt T: 290°C
- Power: 11.9 MW → 12.6 MW

- +30% UA HXs
- +40% UA heaters
- Higher efficiency
- +45% UA HXs
- +25% UA heaters
- +35% UA HXs
- -1 HX
- -1 splitter/mixer
- +40% UA heaters
Benchmark with partial cooling cycle

**Benchmark with partial cooling cycle**

**Higher efficiency**

**Simpler part load control**

40 % UA increase on recuperator

Power block cost : < 3 % increase

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<tr>
<td>Tmax</td>
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<tr>
<td>Pmin</td>
<td>85 bar</td>
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<tr>
<td>η</td>
<td>36.7 %</td>
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<tr>
<td>Exit salt T</td>
<td>290°C</td>
</tr>
<tr>
<td>Power</td>
<td>12.6 MW</td>
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</table>

**Partial cooling**

**Higher compressor efficiency**

Lower efficiency

30 % UA increase for salt heater

12 % PR increase for compressor

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<td>η</td>
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<td>Exit salt T</td>
<td>290°C</td>
</tr>
<tr>
<td>Power</td>
<td>12.4 MW</td>
</tr>
</tbody>
</table>
Benchmark with dual temperature cycle

### Single turbine & preheat

- **Tmax**: 485°C
- **Pmin**: 85 bar
- **η**: 36.7%
- **Exit salt T**: 290°C
- **Power**: 12.6 MW

### Two turbines & staged heating

- **Tmax**: 550 / 410°C
- **Pmin**: 85 bar
- **η**: 38.4%
- **Exit salt T**: 290°C
- **Power**: 13.2 MW

**Higher efficiency**

- LT turbine could drive all comp.

- 15 % UA increase on recuperators
- 90 % UA increase on heaters
- 2 turbines (13 & 6.5 MW)

**More complex layout**

- Mixing for salt freezing protect.?
Selection of studied cycles – final remarks
Final layout considered: intercooled recompression cycle

- Indirect dry cooling system
- Warm CO₂ mixing

Still to be done:
- Shaft design
- Inventory management
- Control system

Existing salt tanks & pump

High temperature test loop
Recuperator temperature approach selection

Techno-economical choice based on Levelized cost of generating heat of 20 to 25 $/MWh

10°C appears reasonable

Preheater salt freezing protection

Flexible protective measure

Mixing of hot warm CO₂ in cold warm CO₂
Increase by 500% preheater UA
Supplier review: first lesson learned

More than 25 suppliers consulted for turbine, compressor and heat recuperator

From China, Japan, Korea, US, UK, Germany, Switzerland & France
Good reception of the request for proposal and constructive/commercial answer

✓ Turbine
- No key issue to design and manufacture but no firm performance guarantee
- Efficiency above 85 % is foreseen
- Radial and Axial design still co-exist at 18 MW

✓ Compressor
- No issue linked to transcritical compression
- Compressor inlet around critical pressure make design dificult (especially combined with high PR)
- Performance guarantee around 80 % for compressors
- Radial design

✓ Heat recuperator
- Almost all suppliers goes for PCHE technology
- No design issue and performance guaranteed

All key equipment can be readily manufactured with obviously some lack of references

Supplier pre-selection to be done end of 2018
Control design and operability

To test control option and detailed design option

Control design based on a fully physical dynamic model of the plant

Part-load control by bypass control

Main compressor inlet temperature control

Molten Salt Outlet Temperature (MSOT) control

Part-load control by inventory control with min P protection

Dynamic model developed in Dymola

Reference: -10% load/minutes

Very fast response speed.

Higher response time compared to single inventory control

Bypass control dominates.

Inventory control dominates.

Higher efficiency compared to single bypass control

Case study: Part-load control: Inventory + bypass control

For more information, see the poster:

Dynamic modeling and part load control strategy of a molten salt heated recompression SCO2 Brayton cycle
Preliminary site implementation proposal

- HT salt loop
- Cooling system
- CO2 storage
- Power block & auxiliaries
Conclusion…for now

Retrofit of 10 MW Shouhang CSP plant in Dunhuang is on the way

- Demonstrator cycle and layout selected
- Supplier reviewed (preselection soon)
- Shaft design and balance of plant before nov.
- Formal feasibility study report by Chinese Design Institute (late 2018)
- Investment decision (early 2019)

For $\text{SCO}_2$ cycle technologies

- Suppliers ready to start real project
- No technical showstopper for design
- Need to dive into control and operation aspect
- Good potential even at medium T
  - Foresee 45% cycle efficiency for commercial at 550°C
Thank you

Any question?