

Particle heat exchanger for the integration of CST into a supercritical CO₂ Brayton power cycle

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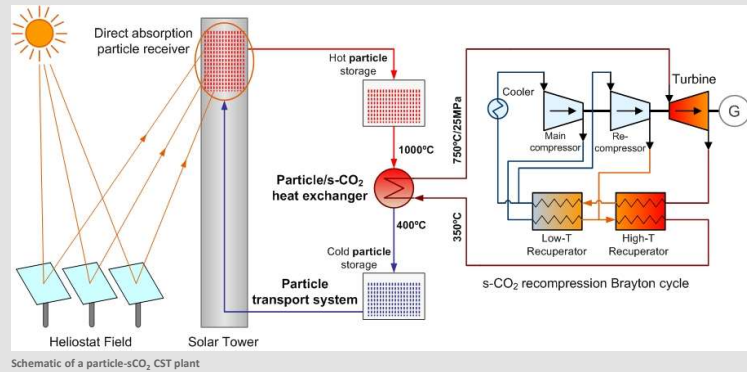
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Introduction

The project COMPASSCO₂ investigated key components required to integrate a CST solar tower plant with a supercritical CO₂ (sCO₂) Brayton power cycle operating at extreme conditions of 700 °C and 250 bar, aimed to achieve an outstanding thermal efficiency of 49%. The project developed and tested

- new solid particles and their coatings for use as heat transfer and thermal storage materials,
- new chromium alloys to be used as bulk material or coatings for the application in a particle/sCO₂ heat exchanger (HEX) and
- a HEX design optimized to increase the heat transfer coefficient between particles and sCO₂.

This poster summarizes the particle/sCO₂ HEX design and tests results.



HEX operation conditions

The HEX tubes must withstand **erosion** caused by particles, **oxidation** and **creep in air** in the exterior. In the interior, surfaces must be resistant to **corrosion** and **creep in sCO₂**. Design conditions include:

- particles at **900 °C**
- sCO₂ at 700 °C and an internal pressure of **250 bar**
- cyclic operation** adds challenges to the material durability.

Due to the extreme operating conditions, the material choice is limited to a few austenitic steels and Ni-based alloys. Beyond commercial materials, **novel chromium superalloys (Cr-NiAl bulk and Cr-Si coating)**, with promising erosion and corrosion resistance, high melting points, low price and exceptional oxidation resistance were developed, produced and tested in COMPASSCO₂ [1] [2].

To transfer the heat from the hot particles to the sCO₂ a **moving bed heat exchanger** was designed. The tube arrangement geometry was optimized to improve the flow distribution. Hot long-term tube tests with particle temperature around 750 °C were done for over 800 h (with air or pressurized nitrogen in the inner tube side).

A mock-up particle/sCO₂ HEX was designed and tested with particles entering between ~450 °C and 650 °C and sCO₂ outlet temperature between ~350 °C and 630 °C.

Performance tests

The operation was done during several days to reach eight different steady states with sufficient information to calculate the HEX performance.

To verify the particle mass flow, measurements were conducted after the experimental campaign at four temperature levels, while the settings for the screw conveyor and transport air were kept identical to those used during the test campaign. A **mean particle mass flow of 0.17 kg/s** was obtained.

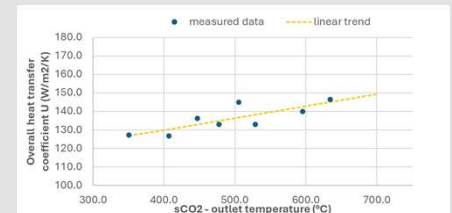
Heat losses of the heat exchanger to the ambient temperature were estimated by running the experimental without sCO₂ flow and letting the heat exchanger cool down naturally; an **average heat loss coefficient of 0.7 W/m²K** was calculated.

The overall heat transfer coefficient was plotted as function of sCO₂ outlet temperature and a linear trend was fitted to the data to predict the thermal performance at higher temperatures. Although the trend shows only a moderate increase with temperature, it suggests that an **overall heat transfer coefficient of 150 W/m²K** could be reached at a sCO₂ outlet temperature of 700 °C.

Results

The inlet temperature of the particles was derived for each steady state starting from 473.8 °C and reaching the **maximum of 667.7 °C**.

The **maximum transferred heat of 20.92 kW** to the sCO₂ flow was reached with sCO₂ inlet and outlet temperatures of 195.4 °C and 350.6 °C, respectively. The **heat losses of 0.5 kW** were significantly lower than transferred heat but increased slightly linearly with the particle inlet temperature. The **overall heat transfer coefficient ranged from 126 to 147 W/m²K** across the different steady states, which is considered relatively high and exceeded the initial estimates.



Relation between the overall heat transfer coefficient and measured outlet temperature of sCO₂.

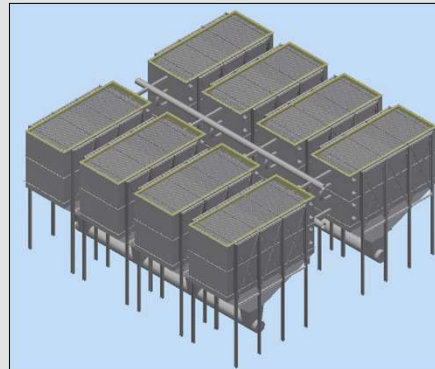
Upscaled design

Based on the HEX tests, the industrial partner John Cockerill Renewables upscaled the design for a potential commercial application in the megawatt scale.

The designed maximum temperature of the heat exchanger tubes is 760 °C based on iterative calculations. This leads to a **maximum allowable stress (MAS) of tubes made of Haynes282 of 86.6 MPa**.

The **tubes bending is a critical criterion** for the design of the heat exchanger. The following conditions need to be considered:

- Bends will have a wall thickness reduction on the outside of the bend of maximum 10.5%;
- Thickness is calculated for an operation pressure of 250 bar (design pressure = 285 bar).



Modular design for the high pressure and low pressure HEX with 8 modules of 15 MWth each. The total dimensions of an 8 modules arrangement are: length 21.4 m, and width 21.7 m and height 11 m and the total weight is 1068 ton.

Conclusions

- The results show a good thermal performance of the heat exchanger.
- The maximum sCO₂ outlet temperature of 634 °C was reached with the particle inlet temperature of 668 °C.
- A maximum heat transfer coefficient of 147 W/m²K was reached during the test.
- The target sCO₂ temperature of 700 °C was not reached due to a heater section failure. However, based on the extrapolated trend, an overall heat transfer coefficient of approximately 150 W/m²K is expected to be achievable at the target temperature. Moreover, addressing the non-uniform particle flow distribution could lead to a significant increase in this value by enabling more effective use of the heat transfer surface.
- It is estimated that a value of around 200 W/m²K can be reached for an optimized set-up.
- The knowledge gained from this project is not only applicable to this use case, but can contribute to the decarbonization of high-temperature industrial applications.

References

- [1] K. Ma, „Chromium-based bcc-superalloys strengthened by iron supplements“, Acta Materialia, Bd. 257, Juli 2023, doi: 10.1016/j.actamat.2023.119183.
- [2] M. Kerbstadt, E. M. Hamilton White and M. C. Galez, „Novel Cr/Si-Slurry Diffusion Coatings for High Temperatures“, Materials, Dez. 2023, doi: 10.3390/ma16237480.

Particle & sCO₂ loop built and tested at CVR's installations in Prague, Czech Republic. View of HEX (bottom) and electrical particle heater (top) without thermal insulation