SUPERCRITICAL CO_2 RANKINE CYCLE TEST LOOP (ROMA) - OPERATION AND INITIAL RESULTS

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Aluminium production in Norway

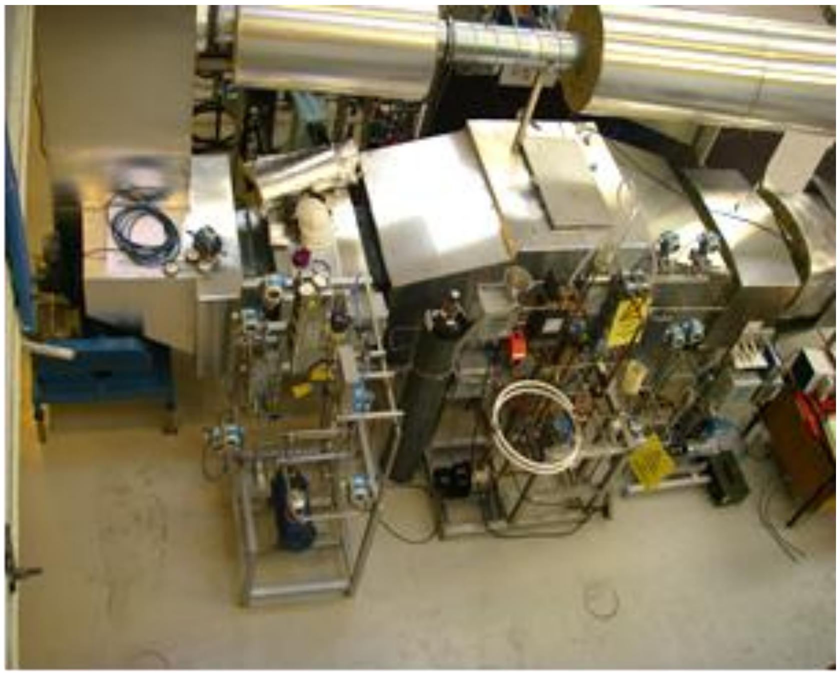
- The aluminium industry has strong focus on process and energy efficiency
  - Competing in international market from high-cost country
  - Green profile important for public and governmental support (tax regimes, etc)
- Aluminium production in Norway utilizes ~25 TWh of electric energy
  - 1/5 of the total national consumption (hydroelectric power)
  - Approximately 50% is chemically bound in the product, the rest is lost as heat to the ambient
  - Remote locations of plants make conversion to electric power attractive
- A major waste heat source is exhaust gas from electrolysis cells (~110-125°C)
  - ~35% of total waste heat

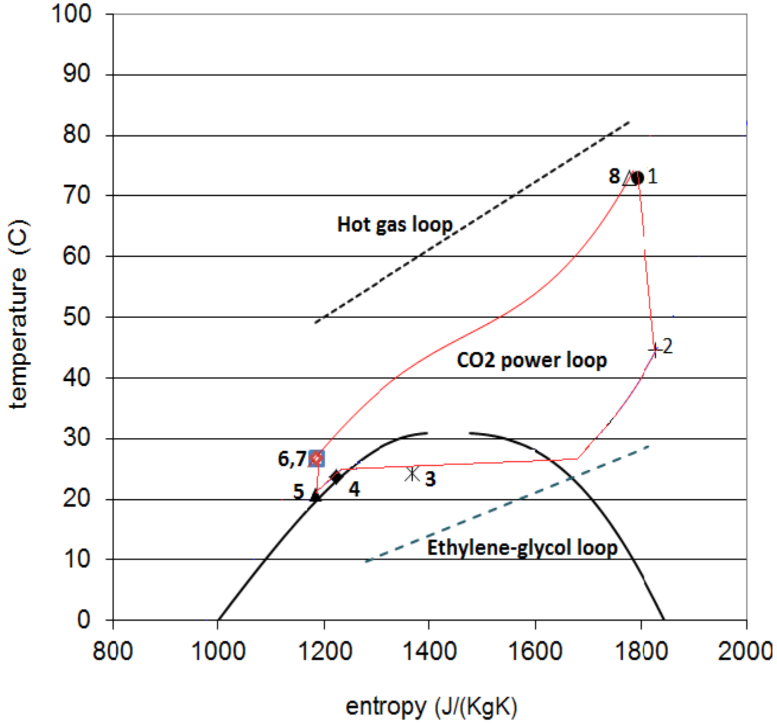
Background: CO_2 working fluid

- SINTEF: Theoretical and practical experience with CO_2 based processes and components for refrigeration, AC and heat pumps since 1987
- The transcritical CO_2 Rankine power cycle: high performance in energy recovering from low temperature sources.
- The transcritical process:
  - Absorbs heat at a supercritical pressure (CO_2 critical pressure 73.8 bar)
  - Exergy losses increase with temperature difference between fluids. CO_2 heated at gliding temperature => better temperature fit , lower exergy losses
  - High pressure cycles => component size reduction and investment cost reduction
- CO_2
  - High performance, low cost, low toxicity, is non-flammable and has no environmental impact.

Built Prototype - ROMA rig

- A CO_2 ORC prototype has been built up in the laboratories of SINTEF/NTNU.
- Heat source: Heated air => ~exhaust heat from aluminium production cells





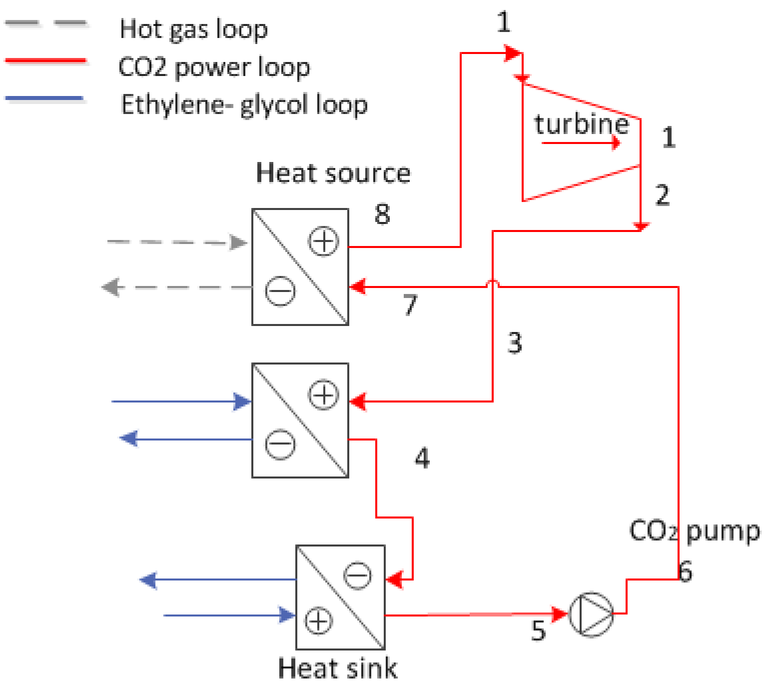
Built Prototype - ROMA rig

Limit values encountered for a normal functioning of the rig

Condens. pressure	Cooling fluid inlet temperature	Heat source temperature	Glycol pump frequency	Global glycol mass flow rate	air mass flow rate	CO2 mass flow rate
58-64 bars	5-12° C	60-110 C	30-50 Hz	5-20 kg/min	12-24 kg/min	1.8 - 4 kg/min

Auxiliary loops

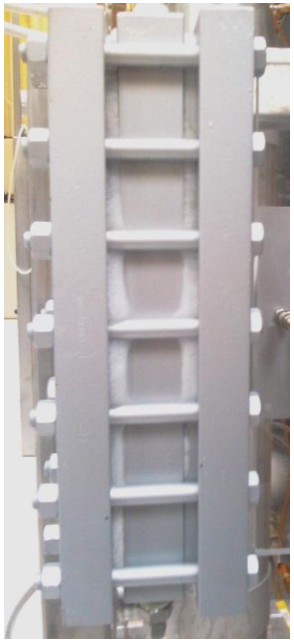
- *Hot gas loop:*
  - Heat source. Represents exhaust flue gas extracted from an aluminum electrolysis cell.
  - About 22 kg/min hot air @ 65, 90 and 110 °C.
  - The heat recovery from the hot air to the CO_2 of the power cycle was performed in a tube-in-fin heat exchanger.



- Ethylene-Glycol loop;
  - Heat sink loop.
  - Up to maximum of 10 kg/min.
  - To control condensation pressure and *sub* cooling (to protect the pump from cavitation) separately, three heat exchangers series connected

CO_2 Power loop

- Component availability was quite challenging in 2008
  - Expander: Special prototype from Obrist Engineering
  - Condensers: Plate HXs (120 bar)
  - Gas heater/WHRU: Custom tube-in-fin



Brazed plate HX with bolted frame

Gen. 2 Gas Heater

Gen. 1 Gas Heater

Expander

- *Expander* The expander is a tailor made prototype
  - Pressure: max 133 bars on HP and 90 bars LP
  - Maximum operating temperature 160 °C
  - Maximum flow rate is 250 kg/h.
  - Maximum 7000 rpm.
  - The expander is connected to a direct current generator. The torque is limited to 5 Nm

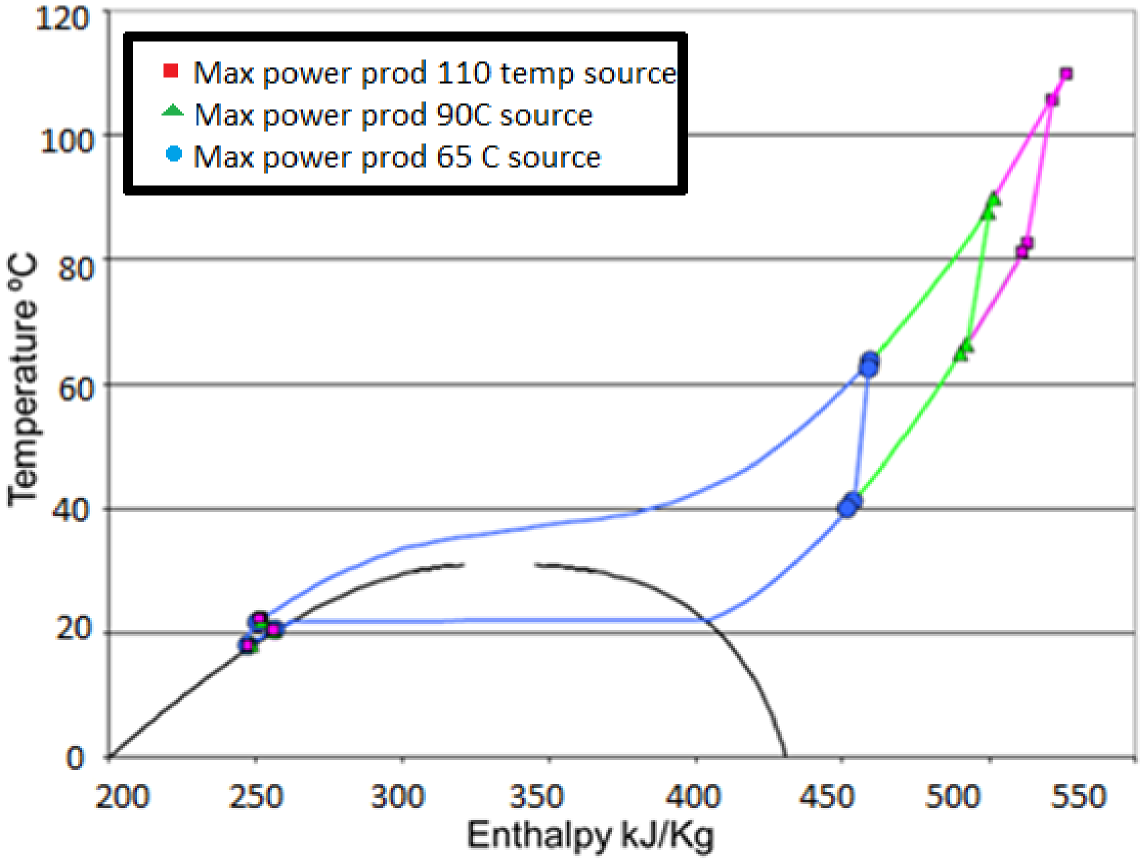
Challenges

- Two-phase fluid in the pump: Added subcooler on receiver. This reduced the inlet pressure to the pump and also the inlet pressure to the expander.

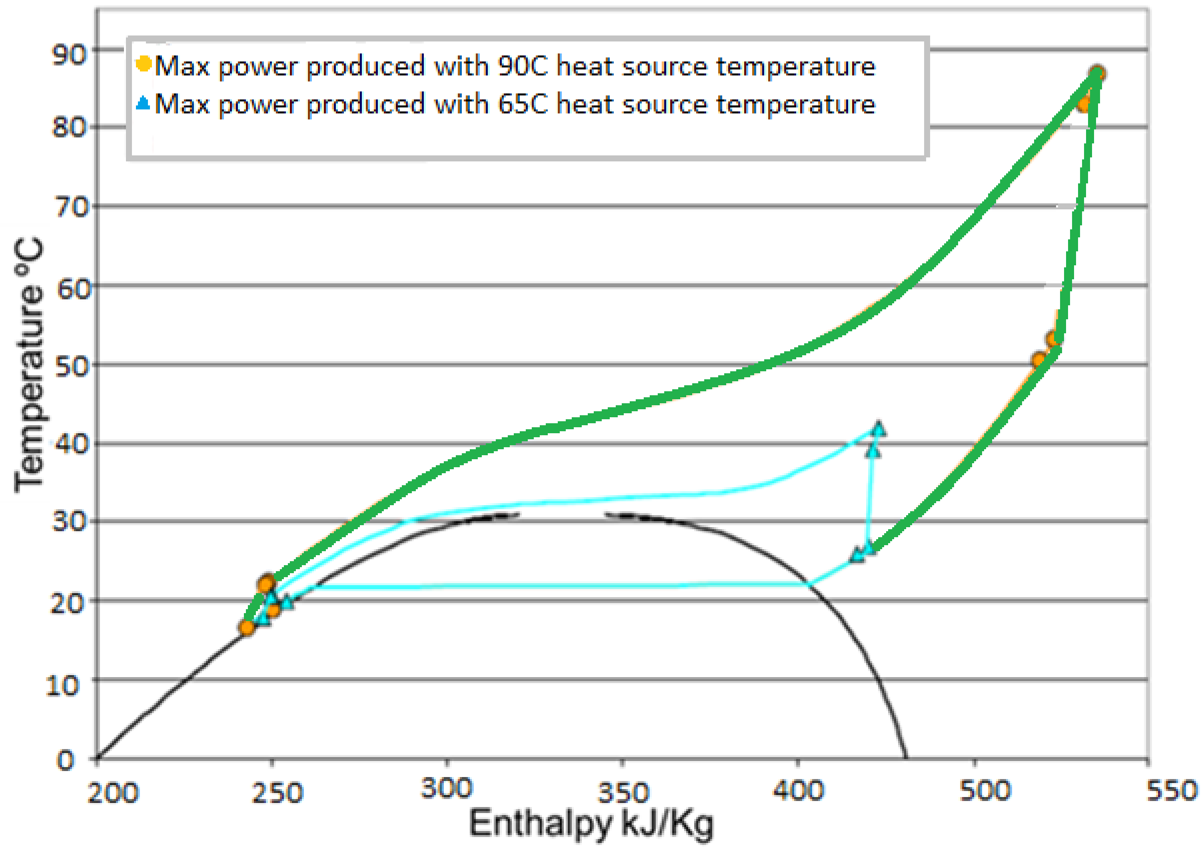
- Heat sink was slightly under dimensioned and heat source temperature had to be limited to 110°C and below as a result.

- Low capacity (and efficiency) expander limited cycle operation.

Test 1: Increasing heat source temperature 65 °C, 90 °C and 110 °C for a constant CO_2 mass flow rate 1.8 kg/min



Test 2: CO_2 mass flow 3.0 kg/min for increasing heat source temperature 65 °C, 90 °C



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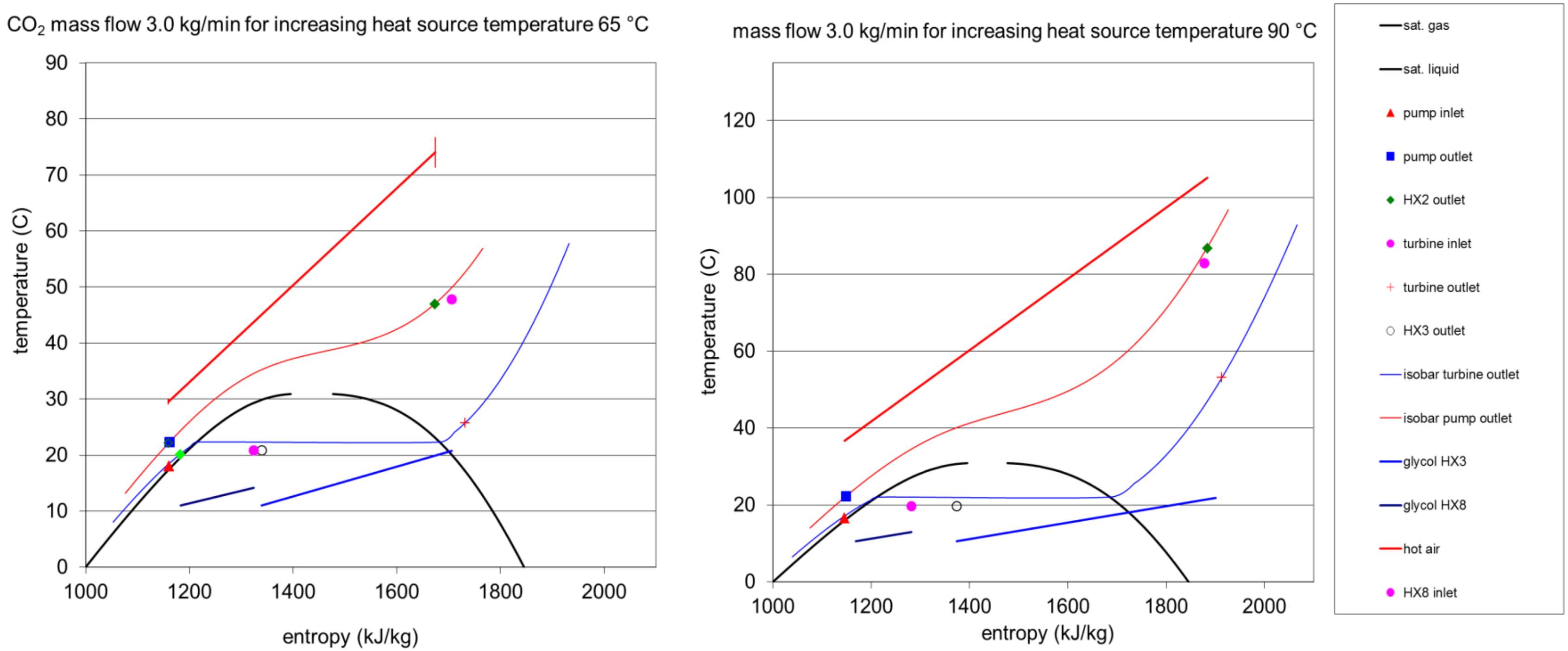
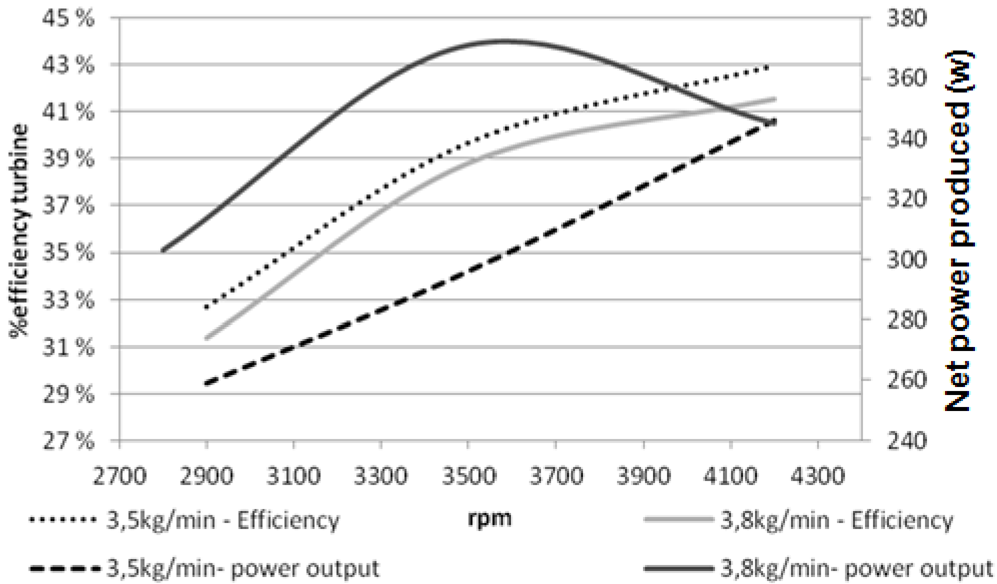


Test 3: CO_2 mass flow 3.5 and 3.8 kg/min for increasing rpm source 80 C

- Efficiency increases with increasing mass flow, until no more heat can be removed
- Expander efficiency typical for small scale expanders



Conclusions

- Experimental results confirm CO_2 to be **suitable** and that the transcritical CO_2 Rankine cycle was operated with **stability and reliability.**

- The system performs as expected from theoretical calculations. Better performance can be achieved:
  - Higher temperature heat source
  - Higher mass flow rate of CO_2 given the possibility to increase the extracted heat and reduce the return temperature of CO_2
- Due to the small size of the expander its performance can be improved. Optimization not part of this experimental campaign.
- The expander prototype has relatively low efficiency – typical for small scale prototypes

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