CoBra – A High-Temperature, Load-Flexible Brayton-Cycle Heat Pump Demonstrator

A. Phong Tran[1], *Johannes Oehler*[2], *Fatma Cansu Yücel*[3], *Panagiotis Stathopoulos*[4]

1 German Aerospace Center (DLR), Institute of Low-Carbon Industrial Processes, Cottbus, Germany, Phong.Tran@dlr.de
2 German Aerospace Center (DLR), Institute of Low-Carbon Industrial Processes, Cottbus, Germany, Johannes.Oehler@dlr.de
3 German Aerospace Center (DLR), Institute of Low-Carbon Industrial Processes, Cottbus, Germany, Fatma.Yuecel@dlr.de
4 German Aerospace Center (DLR), Institute of Low-Carbon Industrial Processes, Cottbus, Germany, Panagiotis.Stathopoulos@dlr.de

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Introduction

The CoBra is a high-temperature heat pump demonstrator utilizing a closed-loop, reverse Brayton cycle. Driven by turbomachinery and using air as a natural working fluid, the system simultaneously provides sensible heat up to 260 °C and cooling down to -25 °C. This demonstrator addresses the demand for industrial heating solutions, particularly for processes requiring high temperatures and large temperature glides, such as industrial drying.

Methods

The CoBra heat pump, developed and commissioned by the German Aerospace Center (DLR), entered its experimental phase in June 2024. [1] The heat pump uses a compression system with two centrifugal turbocompressors in series and an axial turbine for expansion and power recovery. For experimental flexibility, the compressors and the turbine are mounted on separate shafts. Heat transfer is conducted via three shell-and-tube heat exchangers designed for low pressure losses and high effectiveness. Due to the significant thermal mass of these heat exchangers, the system requires a monitored heat-up procedure to prevent structural damage induced by thermal stresses.

Part-load performance is realized through two strategies: compressor speed variation and fluid inventory control. Compressor speed variation adjusts the mass flow rate, pressure ratio, and temperature lift based on turbomachinery characteristics. Fluid inventory control utilizes release and injection valves to modulate the total air mass within the loop. This allows the thermal output to be adapted while maintaining constant system temperatures. Additionally, recuperation can improve both the coefficient of performance (COP) and achievable supply temperature by internally recovering heat between the high- and low-pressure flows. [2]

To manage this dynamic system including its safety constraints, a controller was implemented to control the supply temperature while maintaining safe heat-up rates for the heat exchangers. The development and pre-tuning of this controller were supported by a physics-based Modelica model designed to simulate transient thermodynamic behavior, including thermal inertia and volume dynamics. Calibrated

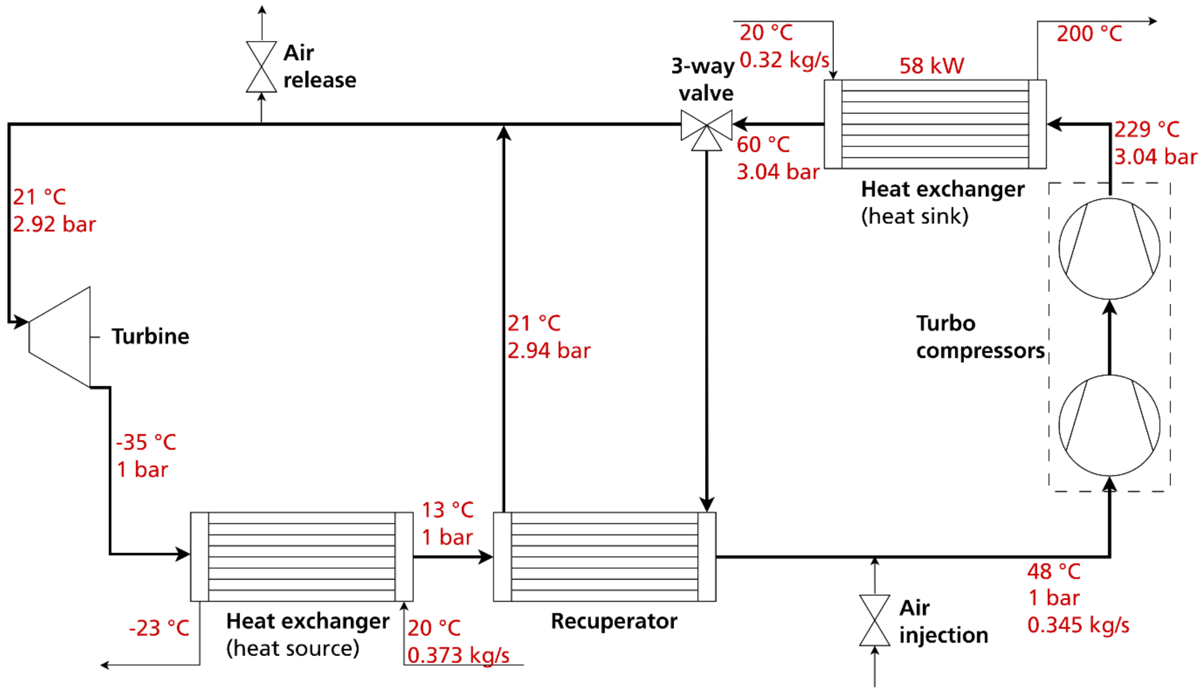

Figure 1: Flow schematic and measured operating point (OP2) with 200 °C supply temperature.

against experimental data, the model achieves mean-normalized root mean squared errors (NRMSE) between 0.12% and 1.46%, providing a validated framework for optimizing start-up and shutdown sequences. [3]

Results and Discussion

Experimentation was conducted on 23 test days, studying steady-state and transient heat pump performance, as well as control performance and part-load capability of the system. Measurement data is publicly available in an open access repository [4]. Figure 1 shows the heat pump flow schematic with temperature, pressure and flow measurements during steady-state operation. During this test, the sink supply temperature was controlled to 200 °C by adjusting the compressor rotational speed. Full recuperation was maintained via the three-way valve to leverage internal heat exchange, which significantly improves system efficiency when a sufficient temperature gradient exists between the high- and low-pressure flows. Under ambient heat source conditions and with an ambient sink inlet temperature, a supply temperature of 200 °C was achieved at a heat supply of 58 kW with a pressure ratio of 3.04. The maximum sink supply temperature reached throughout the experimental phase was 260 °C.

Figure 2 presents an operational envelope showing predicted supply temperatures at a constant sink mass flow rate of 0.32 kg/s as a function of motor speed and compressor inlet pressure (serving as a measure of fluid inventory). The four measured steady-state operating points (OP1–4), each with 200 °C supply temperature, are superimposed on the plot. The close alignment between these points and the model indicates high predictive accuracy.

The supply temperature measurement over time is plotted in Figure 3 showing that the PID controller is able to reject perturbations and maintain the set-point temperature of 200 °C. Ongoing research aims to develop a control system that utilizes compressor speed and fluid inventory to reach target temperatures safely and optimally, using both traditional control methods and Reinforcement Learning.

The results further highlight the different roles of the two control strategies. While compressor speed serves as the primary manipulated variable for supply temperature control, the response is subject to the significant thermal inertia due to the system’s large heat capacities. In contrast, adjusting the fluid inventory proved to be a rapid and effective method for modulating thermal output. Experimental data

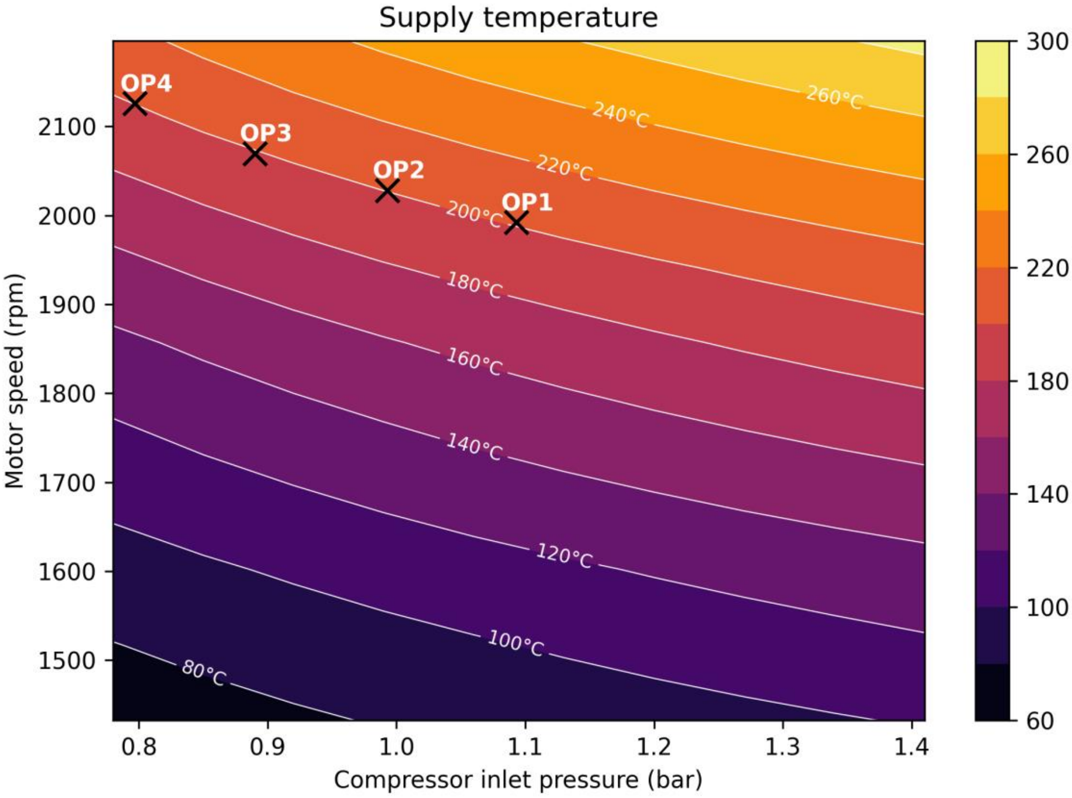

Figure 3: Simulated sink supply temperatures at sink flow rate of 0.32 kg/s for different motor speeds and system pressures. The measured operating points (OP1-4) correspond well with simulations.

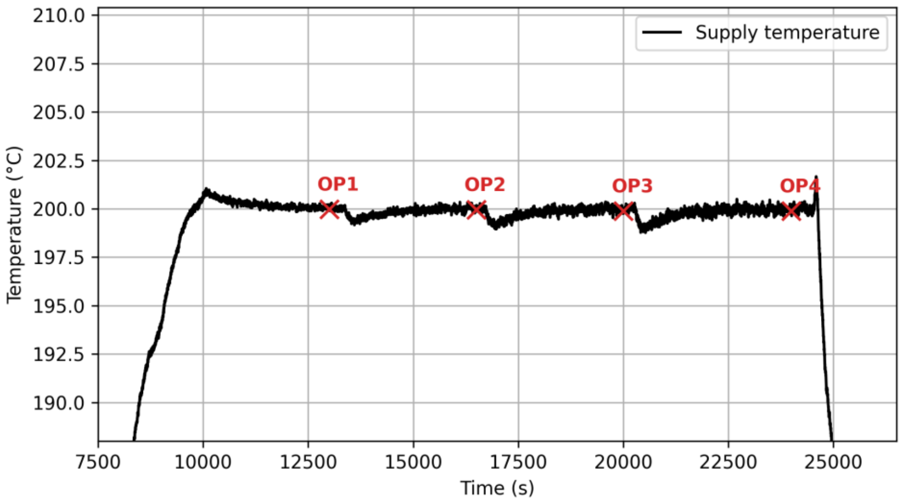

Figure 2: The supply temperature is controlled to 200 °C during the test. The controller rejects perturbations, maintaining stable supply temperature.

demonstrated that fluid inventory control can significantly reduce power consumption within a minute. This fast-acting response suggests that the heat pump is suitable for providing demand-side flexibility, potentially contributing to electrical grid stability.

During the experimental stage, the system exhibited high robustness against common failure modes: The centrifugal compressors showed high aerodynamic stability across a large operating range, including fast transients. The use of dried air as the working fluid prevented icing within the loop, while stresses induced by thermal expansion were mitigated through a combination of expansion loops and control logic.

Conclusions

The experimental campaign of the CoBra demonstrator confirms that a closed-loop reverse Brayton cycle using air is a viable solution for high-temperature industrial heating. By achieving a maximum supply temperature of 260 °C, the system extends the potential field of application of heat pump technology to industrial processes that exceed the temperature limits of currently available systems.

Analysis of the control strategies reveals that while compressor speed regulates supply temperature, fluid inventory control provides a fast method for modulating thermal output. This fast-acting capability, combined with the aerodynamic stability of the turbocompressors and the system's resilience against thermal stress and icing even during transients, makes the technology well-suited for providing demand-side flexibility.

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