Advanced Thermodynamic Cycles for the Energy Transition:
Transient Modelling and Control of High-Temperature Heat Pumps

Phd board meeting – Summary of the 2nd year activity – January 9, 2024

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Abstract

In support of the energy transition, research is focusing on the development of new cycles for the conversion of renewable energy sources (i.e., geothermal, concentrated solar, and biomass), the decarbonisation of conventional ones (fossil), and the improvement of the efficiency and flexibility of existing traditional plants to facilitate the integration into energy networks dominated by largely non-programmable renewable sources. This research project aims to assess the potential of innovative cycles recently proposed in the literature (i.e., high-temperature heat pumps and SCO2 plants). To this extent, comprehensive thermodynamic models of the systems will be developed, accounting also for heat exchangers and piping thermal inertia and rotor dynamics effects. Factors such as optimal configurations, the criticality of machines and components, energy efficiency, and cost will be then evaluated to assess the maturity of the technology. Moreover, novel regulation techniques, enabled by the intrinsic nature of these cycles (i.e., closed cycles), will be investigated throughout the project to guarantee safe operation throughout nominal, off-design, and transient conditions.

1. Case study: CoBra prototype

Key features (non-recuperated layout):

- sink heat temperature of 262 °C
- mean temperature lift of 122 °C
- COP of about 1.31

Control architectures:

- anti-surge control (ASC)
- compressor speed control (SC)
- fluid inventory control (IC)

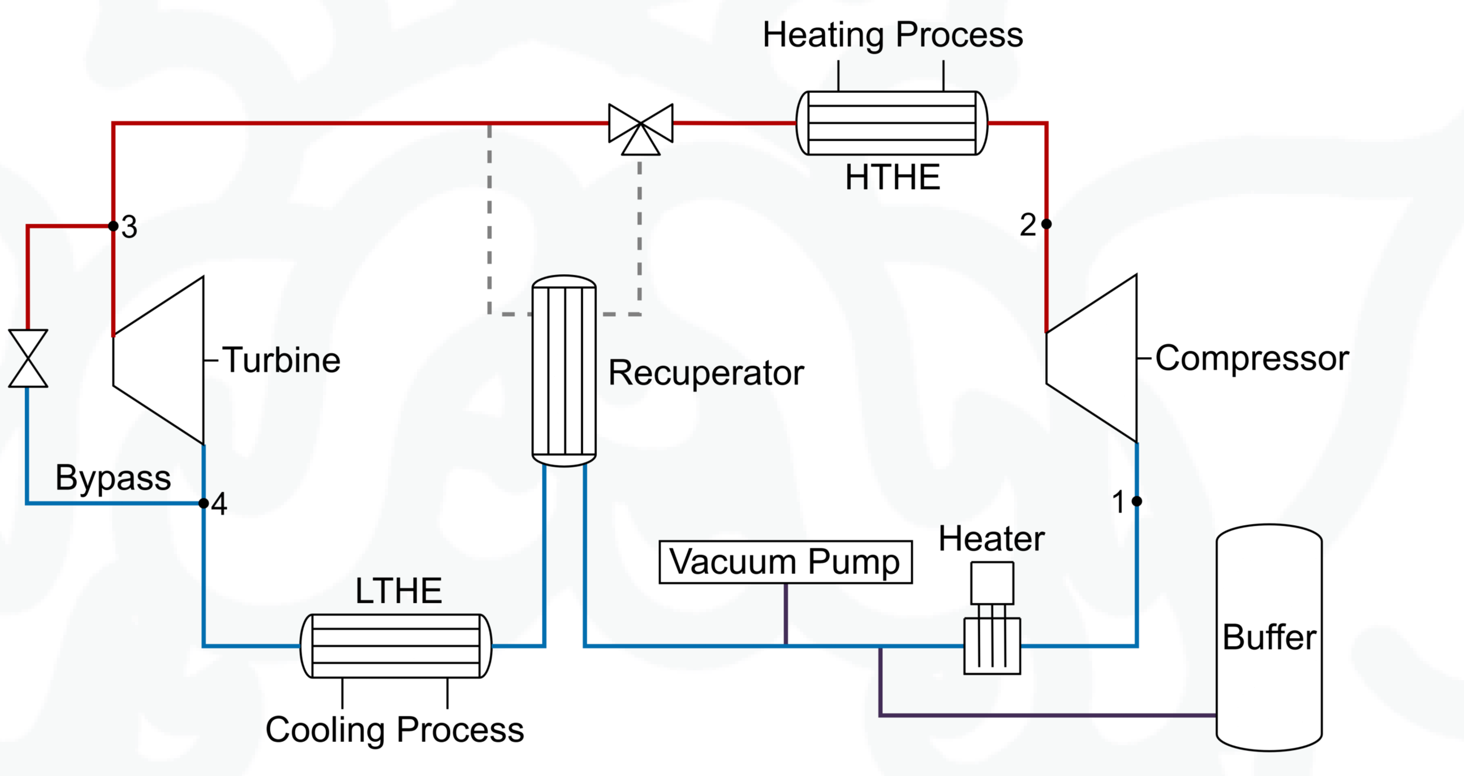

Figure 1: Simplified schematic of the Brayton-based high-temperature heat pump developed by the DLR Institute of Low Carbon Industrial Processes [1].

2. Cold start-up

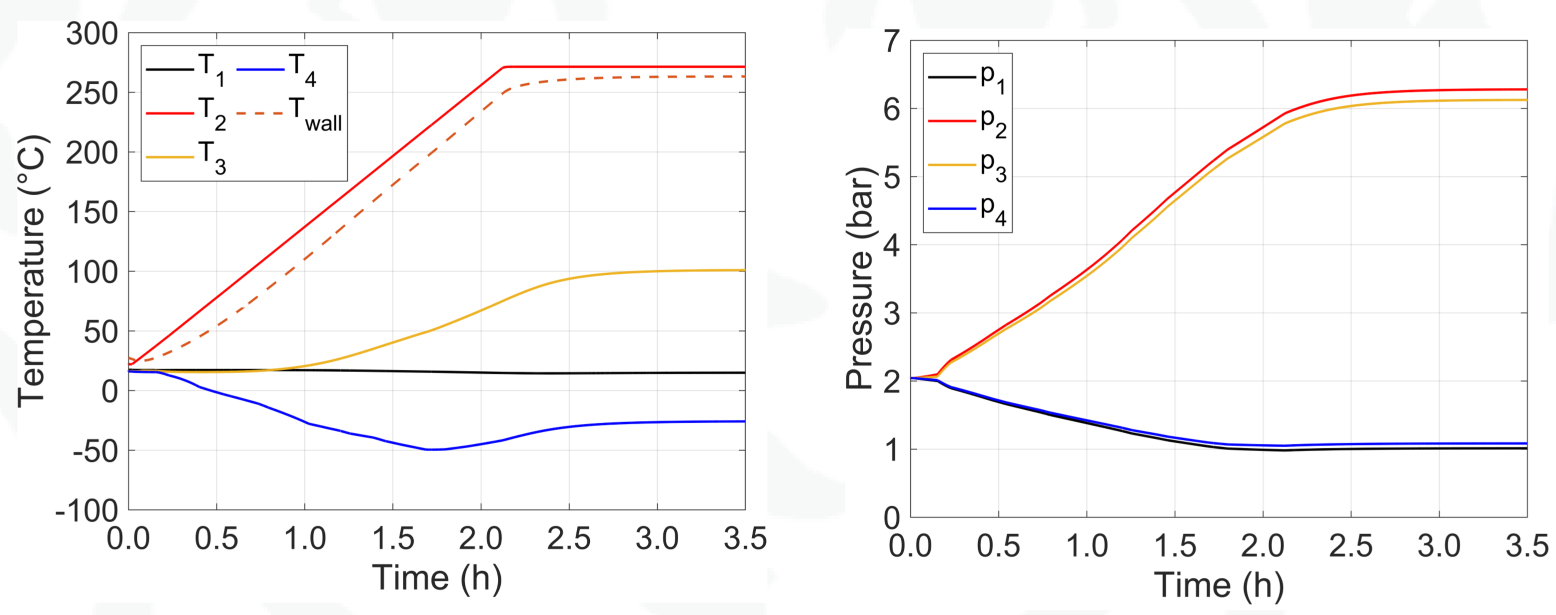

Figure 2: Cycle temperatures and pressure during a cold start-up. The system takes approximately 2 hours to perform a cold start-up. The temperature rate constrain ($\dot{T}_2$) of 2 K/min, used within the SC to avoid thermal stresses at the HTHE, limits the compressor shaft acceleration and the overall system evolution during the manoeuvre. The thermal inertia of the HTHE and piping can be quantified in a delay of 40 min.

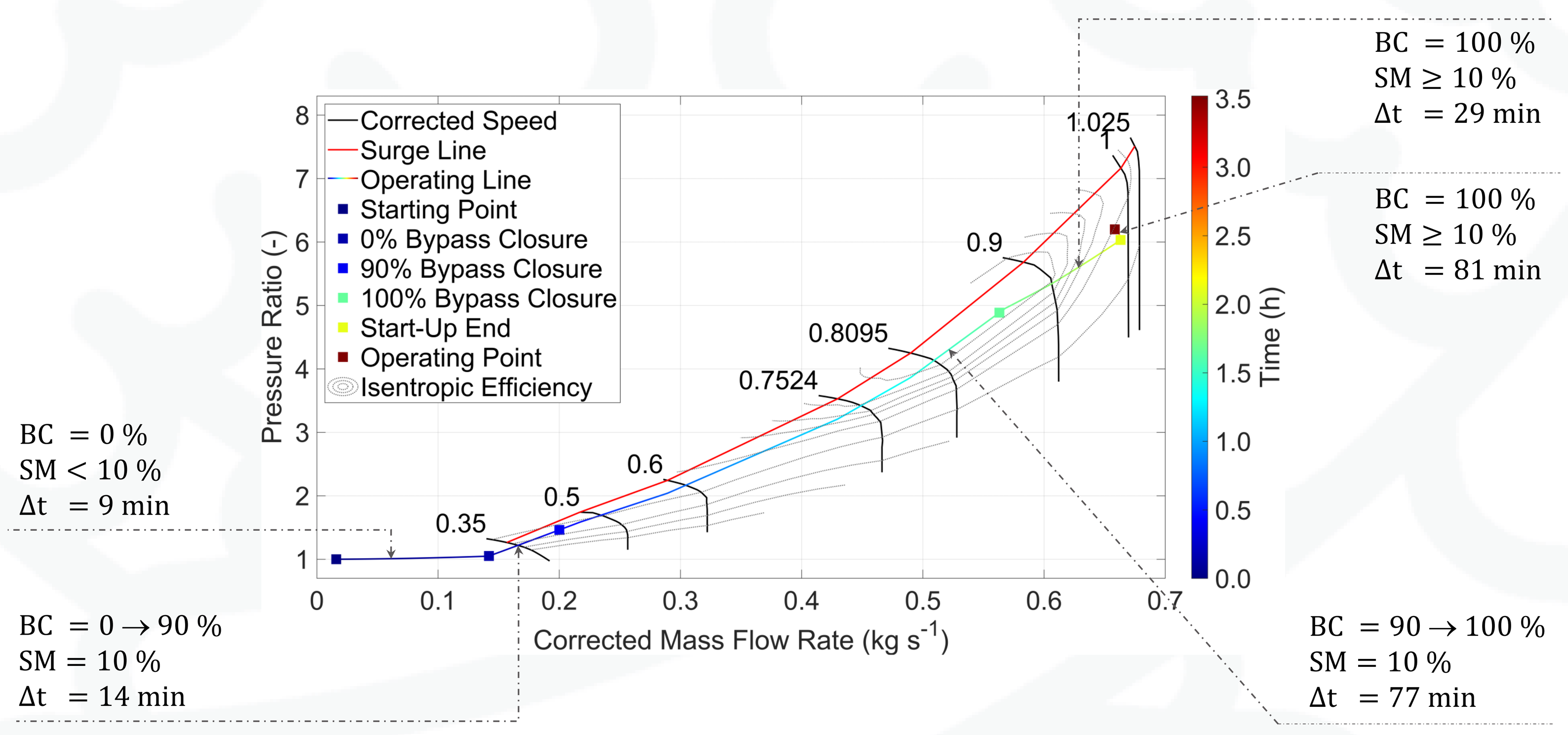

Figure 3: Compressor operating line during a cold start-up. At the beginning of the manoeuvre, the turbine bypass is fully open to avoid compressor surge, and the operating point moves towards higher speeds at an almost constant pressure ratio. Starting from t = 9 min, the ASC gradually closes the turbine bypass to ensure a surge margin (SM) of 10 %. The operating point moves parallel to the surge line. At t = 1.67 h, the turbine bypass is fully closed as the SM is greater than 10 %, and the start-up ends at t = 2.10 h. From there on, the operating point performs a minor displacement due to the stabilization of the cycle temperatures.

3. Sensitivity to $\dot{T}_2$

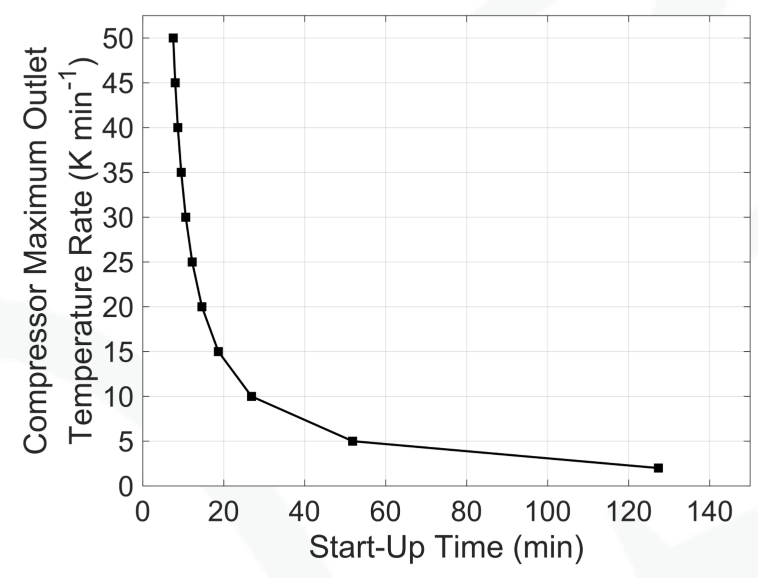

Figure 4: Start-up time for different allowed temperature rates at the compressor outlet. The start-up time significantly decreases when higher thermal stresses are allowed at the HTHE. Minor advantages are observed for rates higher than 10 K/min.

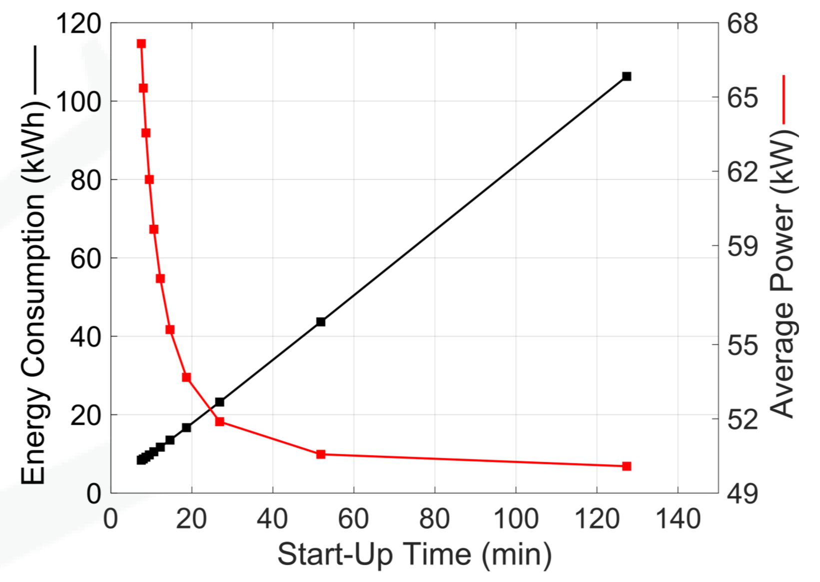

Figure 5: HTHP energy consumption and average absorbed power during a cold start-up for different allowed temperature rates at the compressor outlet. Higher temperature rates cause a lower energy consumption but a higher power absorption.

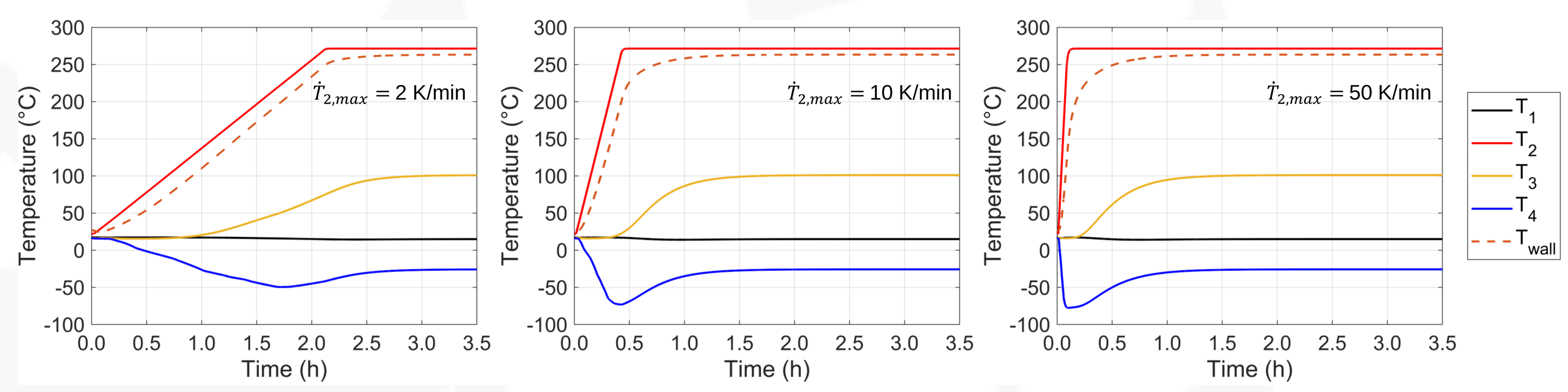

Figure 6: Cycle temperatures and pressure for different allowed temperature rates at the compressor outlet. Higher rates induce faster shaft accelerations and temperature increments at the compressor outlet, resulting in faster manoeuvres. However, as the turbine bypass closes sooner while the turbine inlet temperature remains constant due to the HTHE thermal inertia, the turbine speed must be regulated to prevent icing at the turbine outlet.

Conclusions and forthcoming activities

Findings:

- The present study investigates the cold start-up of a novel Brayton-based HTHP.
- The system takes about 2 h and 9 min to reach design operating conditions.
- The maximum allowed temperature rate of 2 K/min primarily constrains the start-up time of the system.
- Higher allowed temperature rates lead to faster manoeuvres → start-up time reduction of 50 % and 80 % when considering maximum rates of 5 K/min and 10 K/min, respectively.
- Quicker start-ups can induce icing at the turbine outlet → the turbine speed must be regulated during the first phases of the manoeuvre.

Future work:

- Model validation with experimental data.
- Cold start-up analysis while enabling fluid inventory control for mass extraction/addition to the closed cycle.
- Analysis of the transient and part-load behaviour of the HTHP during thermal load regulation [2,3].
- Development of a combined control approach suited to find optimal control trajectories that maximize the system's coefficient of performance while ensuring safe operation (e.g., start-ups, thermal load adjustments).

Acknowledgements

This research has received financial contribution from the Italian Operative National Plan (Piano Operativo Nazionale, PON) in the framework of the project Ricerca e Innovazione 2014−2020 (PON R&I) – Azioni IV.4 e IV.5 "Dottorati di ricerca su tematiche dell'innovazione e green" (DM MUR 1061/2022) e IV.6 "Contratti di ricerca su tematiche dell'innovazione e green" (DM MUR 1062/2022)

References

[1] Ferrari, L., Pettinari, M., Frate, G. F., Tran, A. P., Oehler, J., and Stathopoulos, P., 2023, "Transient Analysis and Control of a Brayton Heat Pump During Start-Up," *36th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2023)*, ECOS 2023, Las Palmas De Gran Canaria, Spain, pp. 839–850. https://doi.org/10.52202/069564-0076.

[2] Pettinari, M., Frate, G. F., Tran, A. P., Oehler, J., Stathopoulos, P., Kyprianidis, K., and Ferrari, L., "Impact of The Regulation Strategy on the Transient Behavior of a Brayton Heat Pump," Energies. (under consideration)

[3] Pettinari, M., Frate, G. F., Ferrari, L., Yücel, F. C., Tran, A. P., Stathopoulos, P., and Kyprianidis, K., "Thermal Load Control in High-Temperature Heat Pumps: A Comparative Study," *GT2024*, London, United Kingdom. (under consideration)