Numerical study of the part load operation for a reverse Brayton high-temperature heat pump

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Institute of Low-Carbon Industrial Processes

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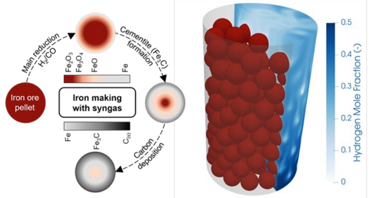
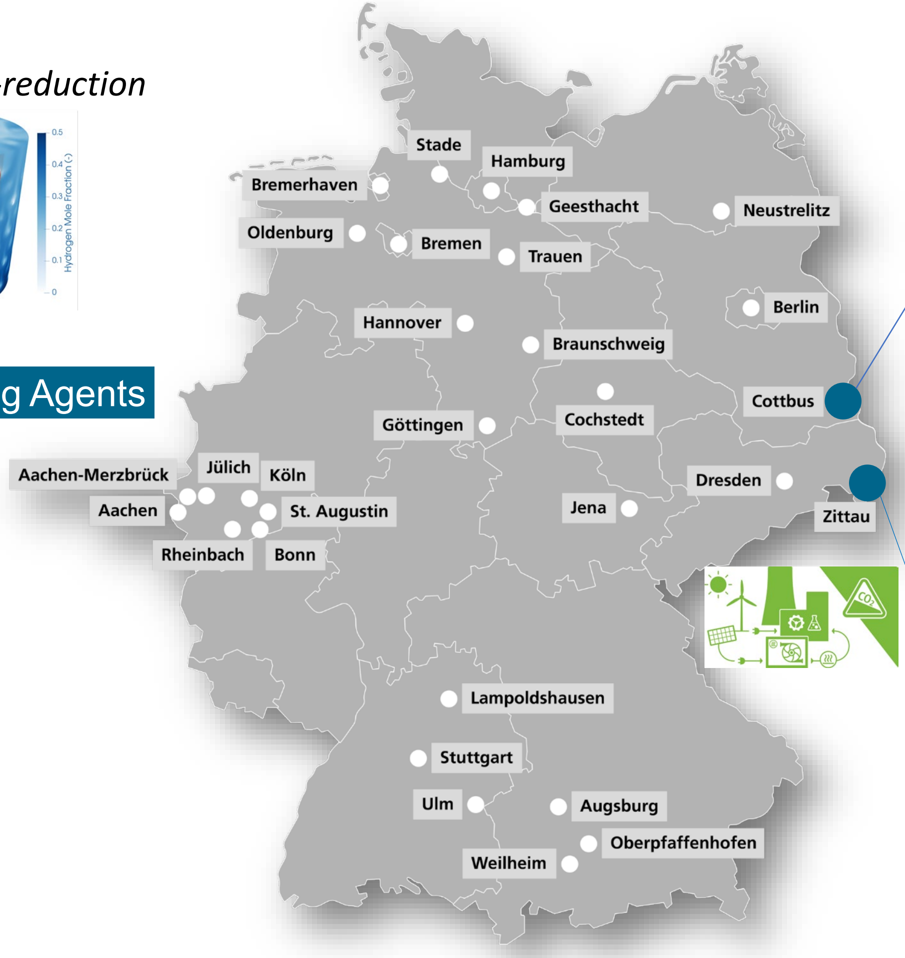


Low Carbon Reducing Agents

Efficiency increase/Risk minimisation

Simulation and Virtual Design



University Library Cottbus

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High-temperature heat pumps in the DLR

High-temperature heat pumps in the DLR

Development goals

- Industry-relevant performance data: 100 kW – n*10 MW
- Useful temperature: 200 - 400 °C (special cases up to 600 °C)
- High COP, depending on waste heat and process temperatures

Cycles and refrigerants

- Brayton cycle - air, inert gases
- Rankine cycle - water, vapor

Process optimization

- Simultaneous optimization of component and process design
- Control concept development and testing

➢ **Part of the research results presented here**

Figure: Test facility of CoBra in Cottbus under construction

Construction of experimental facilities

- Brayton cycle in Cottbus/ Germany (CoBra)
- Rankine cycle in Zittau/ Germany (ZiRa)

Contribution to partial load operation of HTHPs

Contribution to partial load operation of HTHPs

Why Brayton cycle as HTHP technology?

- Simultaneous generation of process heat and cooling
- Very fast capacity control with fluid inventory control
- Examples of potential applications:
  - Drying process, e.g. in the food or construction industry
  - Preheating process, e.g. in the metal or construction industry

Why partial load operation is investigated?

- Major part of operational flexibility of industrial processes
  - Manufacturing conditions, e.g. continuous and batch processing
  - Product conditions, e.g. different product lines
- Until now a drawback of HTHP when compared to direct electric heaters

Contribution to partial load operation of HTHPs

Brayton HTHP Prototype CoBra

- Reverse, closed-loop and recuperated Brayton cycle
- Design features for experimental freedom:
  - Designed for two working fluids - air and argon
  - Compressor and turbine with own shafts
  - Three-way-valve to vary the recuperation
  - Flexible secondary cycles of heat sink and heat source
  - Electrical heater to simulate waste heat temperatures
  - Fluid inventory control - vary the working fluid mass

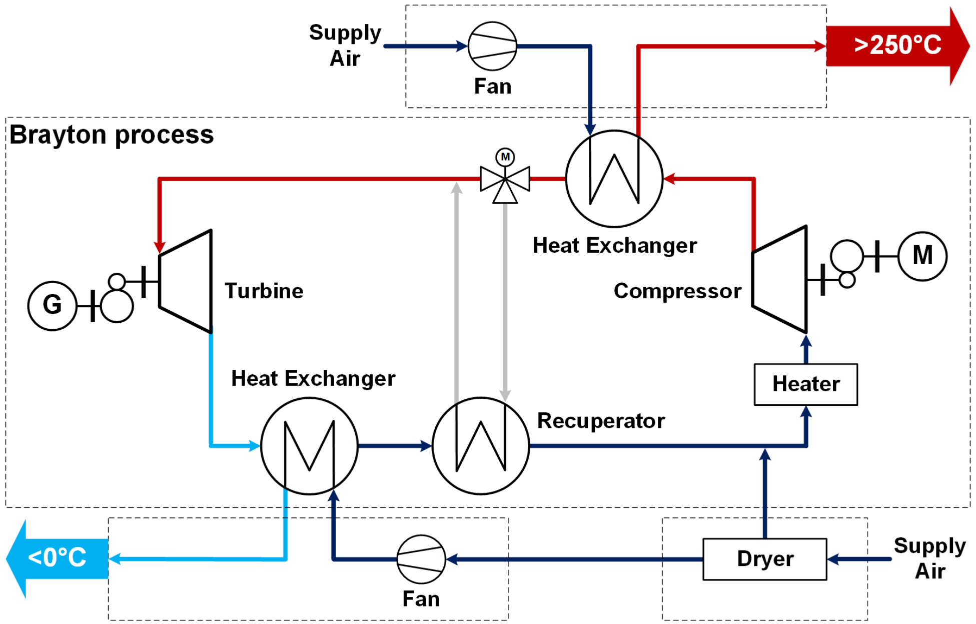

Figure: Simplified scheme of the Prototype CoBra

Contribution to partial load operation of HTHPs

Part load study – Methodology

- EBSILON® Professional simulation model of the Prototype CoBra to investigate the steady-state operation points
- Two integration scenarios
  1. Brayton HTHP with CoBra boundary conditions → ambient air (15 °C) @ heat source inlet
  2. Brayton HTHP for a asumed industrial process with waste heat recovery → 50 °C @ heat source inlet
- Two scenarios of operating range
  - HTHP load 60 – 100 % (100% is equal to 120 kW_{th}) → variation of heat sink mass flow
  - Non-recuperated and recuperated
  - Variable speed of compressor

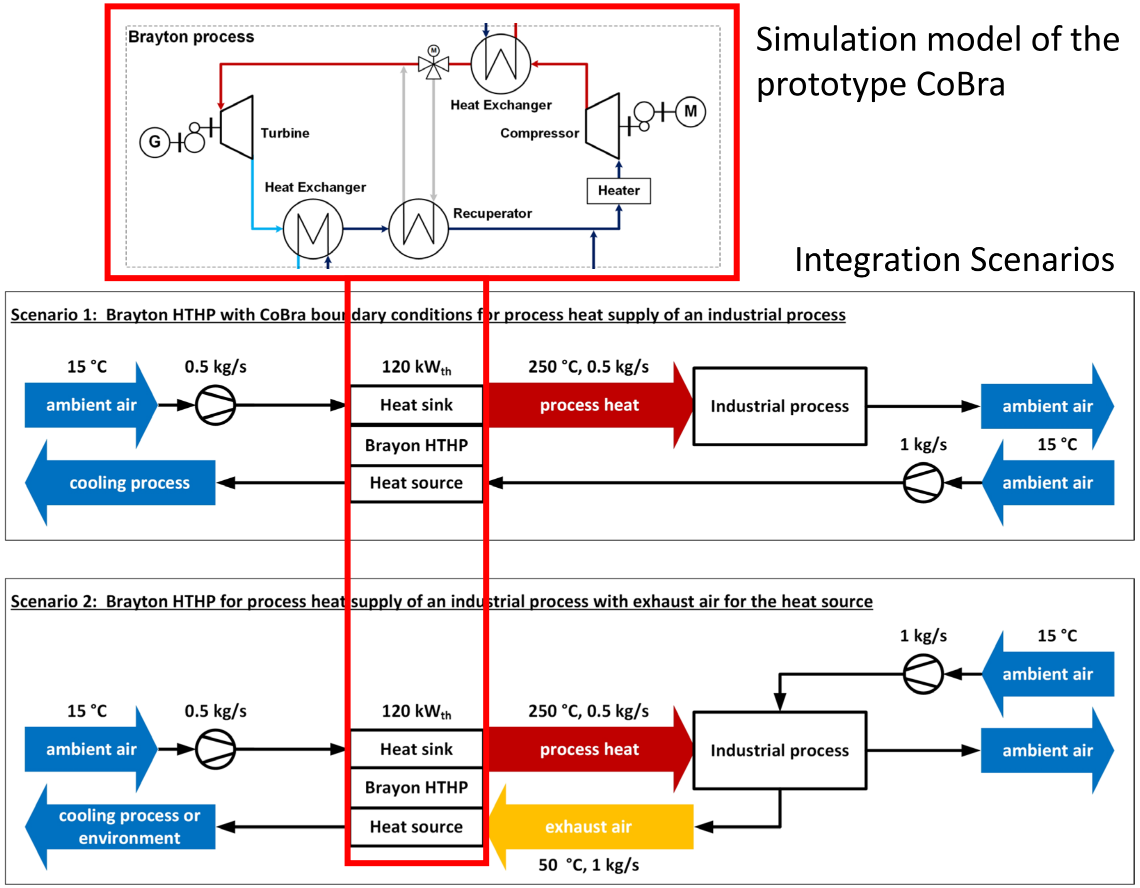

Figure: Methodology of the study

Contribution to partial load operation of HTHPs

Part load study – Results (1/2)

- Scenario 2 has a higher efficiency than Scenario 1 at all load conditions
- Expected increase in COP at low inlet temperatures and increasing recuperation level
- Benefits of recuperation cancelled out as inlet temperature rises

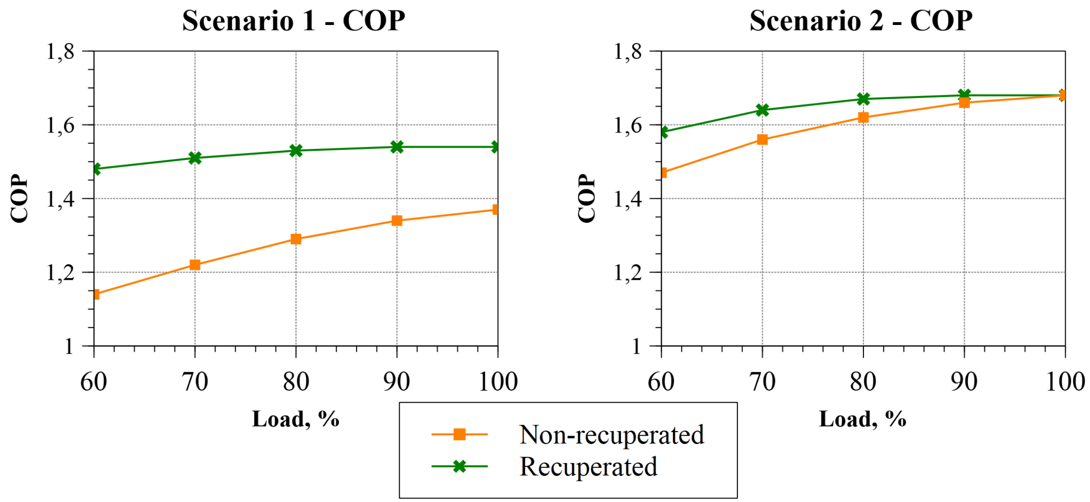

Figure: COP of both integration scenarios

Contribution to partial load operation of HTHPs

Part load study – Results (2/2)

- Wide range of process heat flows are possible when the heat source inlet temperature is not high
- Type of process integration is critical to the intended application
  - Outlet temperature drops significantly at lower heat source inlet temperatures
  - No waste heat necessary when low temperatures are required

➢ If cooling is not required, no recuperation and high heat source inlet temperatures are recommended

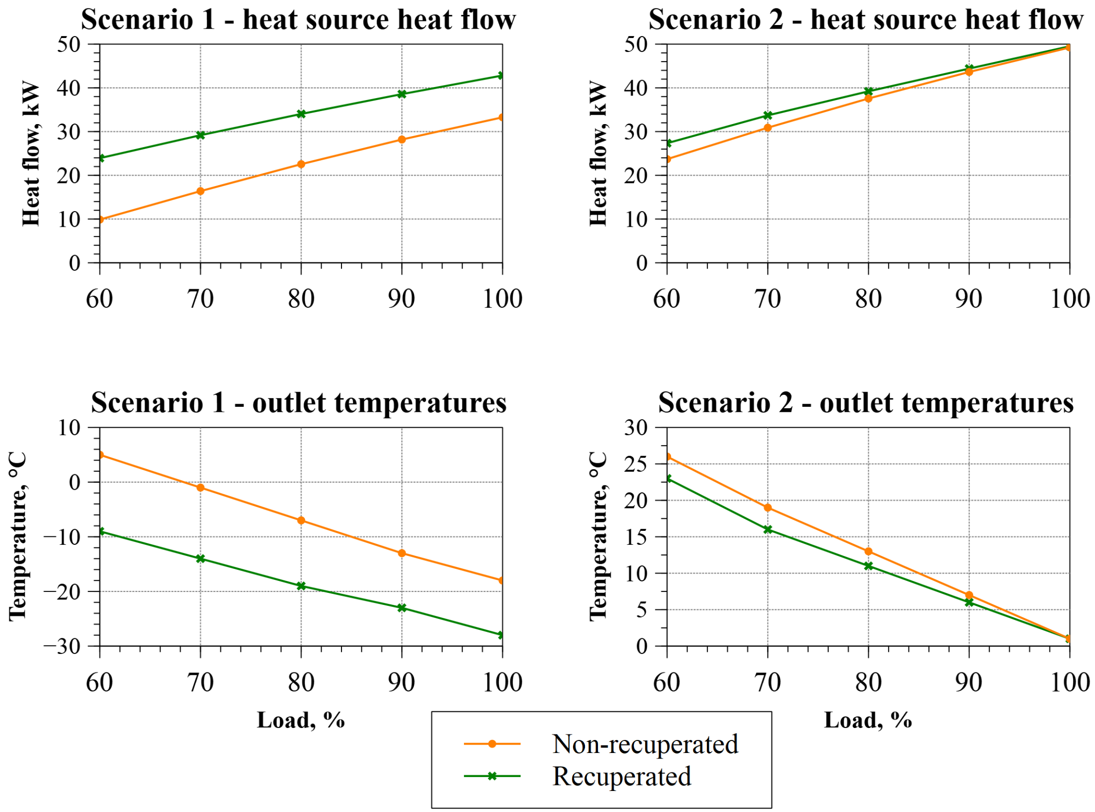

Figure: heat source conditions of both integration scenarios

Conclusion and Outlook

Conclusion and Outlook

Conclusions

- A partial load capable simulation model based on a Brayton HTHP prototype was developed.
- The modelling of part load capable simulation models and the investigations are very complex and time consuming, but can be rewarding in terms of optimal process architecture of the heat pump as well as the process integration.

Outlook

- Other variations of part load considerations are possible, the methodology can be taken from these study, e.g.:
  - Fluid inventory control by actively controlling the working fluid mass in the cycle
  - Electric heater upstream of compressor as an example of additional integration of waste heat recovery
- Running the pilot plant at part load, validating and verifying the simulation based on the test results.

Thank you for your Attention

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Figure: Cobra-mascot on the Brayton prototype CoBra

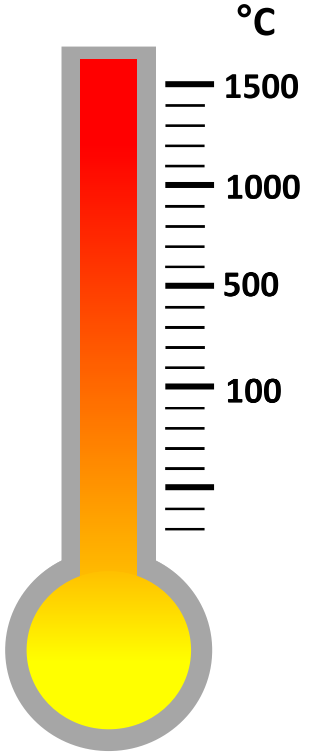
Back-up slides

High-temperature heat pumps in the DLR

Why HTHP technology?

High-temperature heat pumps are seen as a key technology for efficiently using electricity from renewable energies in industry

temperature ranges | **Technological solutions**



„Electrons" → Electricity

„Molecules" → H_2, Carbon-free energy carriers

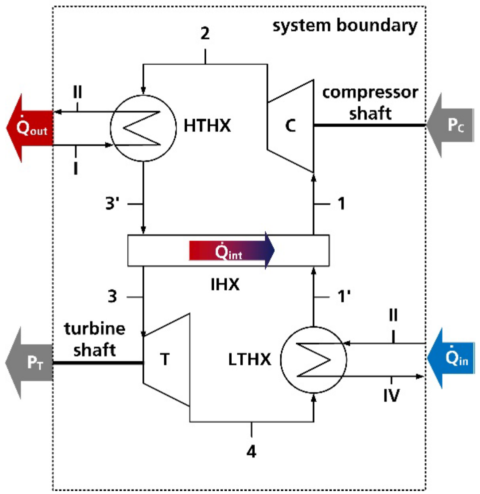
High-Temperature heat pumps

Conventional heat pumps

Figure: „Thermometer" of the Future Process Heat Supply

Brayton process

- By absorbing mechanical power from the compressor shaft (P_c), the compressor (C) raises pressure and temperature of the working fluid (1 → 2)
- The high-temperature heat exchanger (HTHX) transfers sensible heat ($\dot{Q}_{out}$) to the heat sink and cools down the working fluid (2 → 3')
- If the cycle uses recuperation, heat is transferred ($\dot{Q}_{int}$) over an internal heat exchanger (IHX) to further reduce the temperature of the working fluid (3' → 3) before it expands through a turbine
- The output mechanical power of the turbine (P_T) is used to partially drive the compressor. After expansion the working fluid pressure drops to the initial level while its temperature decreases significantly (3 → 4)
- Finally, the working fluid absorbs heat ($\dot{Q}_{in}$, 4 → 1') first from the environment in the low-temperature heat exchanger (LTHX) and subsequently from the fluid exiting the HTHX in the internal heat transfer of the IHX (3' → 1) to close the cycle.



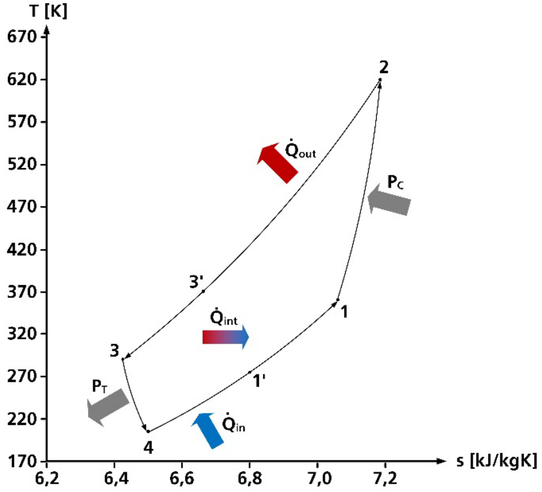


Figure: Scheme of the recuperated Brayton process (above) and sketched T-s-diagram of the simulation model of the CoBra (below)

Coefficient of Performance (COP): $$COP = \frac{\dot{Q}_{out}}{P_C - P_T}$$

DLR-HTHP Prototype CoBra

Design features of the Brayton HTHP Prototype CoBra

- Designed for two working fluids - air and argon
- Compressor and turbine with own shafts and coupled to their electric machines through gearboxes
- Three-way-valve (3WV) to vary the mass flow of the hot fluid entering the recuperator
- Electrical heater upstream of the compressor to simulate an additional waste heat application
- Fluid inventory control by actively controlling the working fluid mass in the cycle
- Simultaneous supply of process heating and cooling
- Flexible secondary heat sink circuit to experimentally simulate various industrial processes / customers
- Flexible secondary heat source circuit with controllable fan and electrical heater as heat source to simulate an industrial cooling process with waste heat recovery

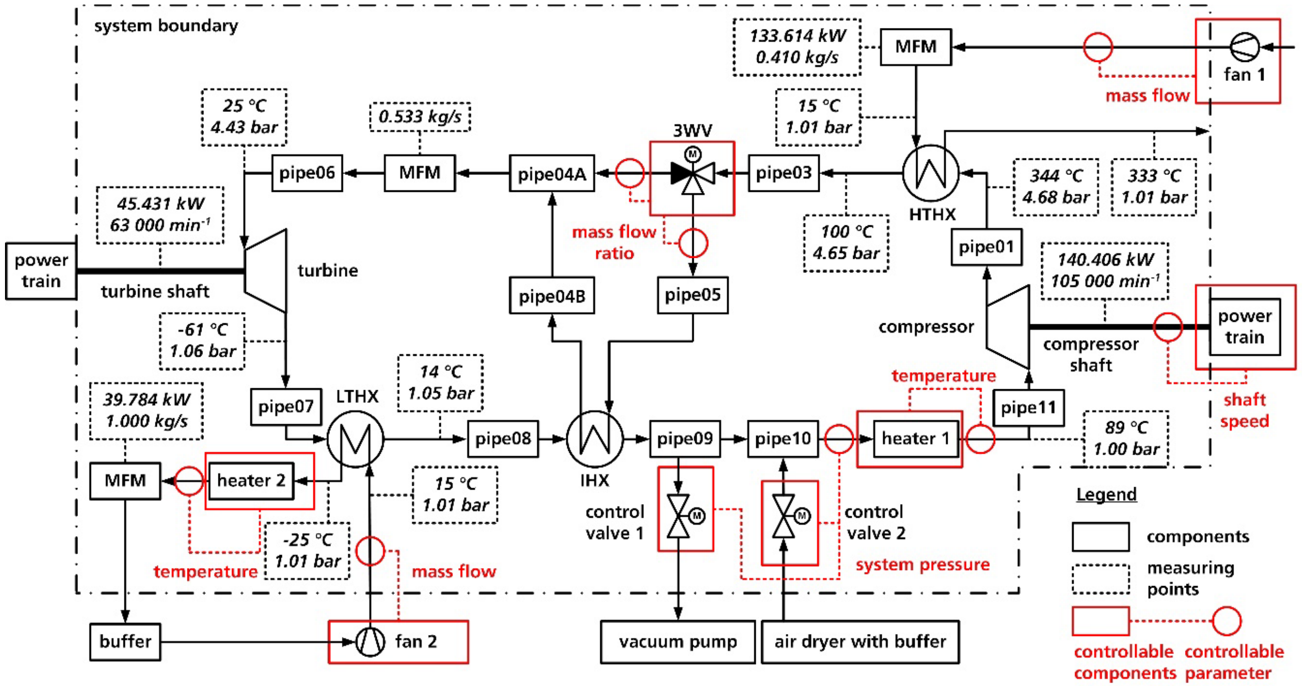


Figure: Scheme of the recuperated simulation model with design parameter (black dotted line) and controllable components (red line)

Simulation model of the Brayton HTHP

Features of the simulation model

- The compressor operation has been modelled with its operational maps
- The reduced mass flow rate in the turbine is considered constant. In other words, it is assumed that the turbine is always operating in the chocked region of its operational map.
- Heat exchanger with exchange surfaces and a standard map for off-design in EBSILON®
- Pipes with geometric based pressure losses and heat losses
- 3WV, electrical heater and MFM (based on CoBra) with constant pressure losses

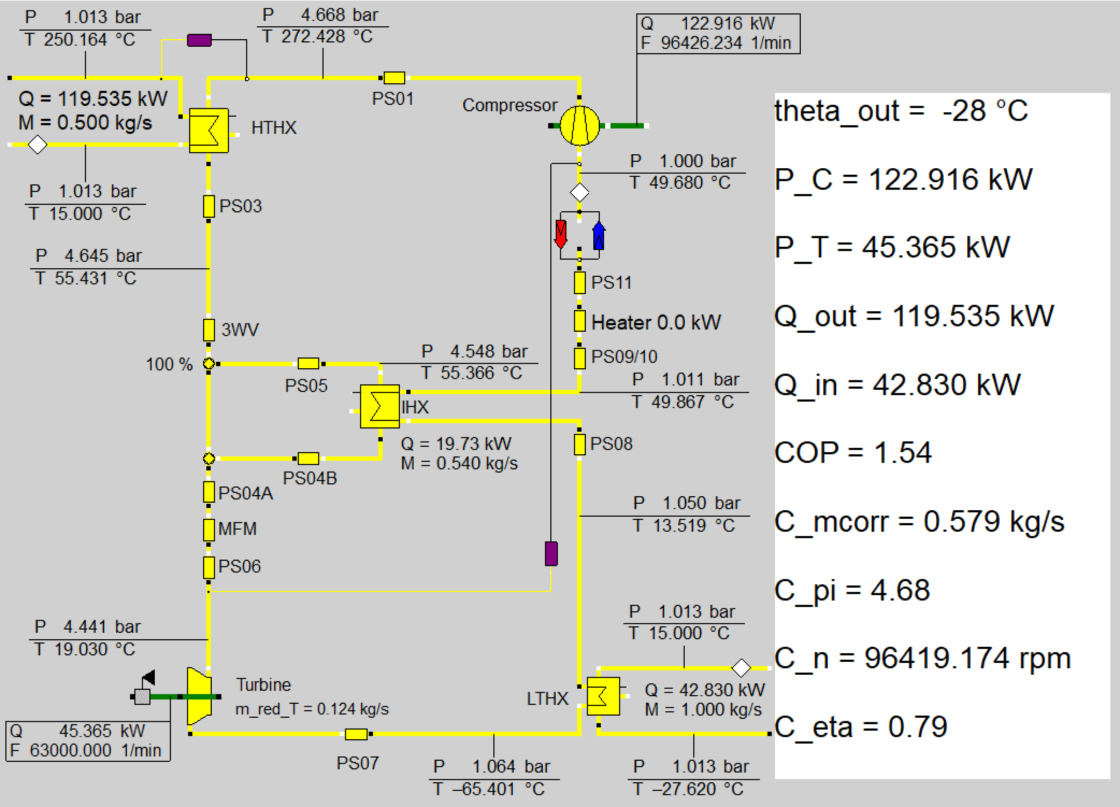


Figure: Example of the EBSILON® Professional simulation model

Simulation model of the Brayton HTHP

Operating limits and ranges of the controllable components of the CoBra

Components	Control parameter	Operating limits	Operating range
Compressor	Compressor shaft speed	Surge and choke limit of the compressor	Map specific
		Maximum shaft speed	max. 105 000 min^{-1}
3WV	Mass flow rate of hot fluid into recuperator	Limits of 3WV	0 … 100 %
Fan 1	Mass flow rate at heat sink secondary	Maximum delivery rate	max. 0.67 kg/s
Fan 2	Mass flow rate of heat source secondary	Maximum delivery rate	max. 1.2 kg/s
Heater 1	Compressor inlet temperature	Maximum compressor inlet temperature	max. 100 °C
Heater 2	Heat source inlet temperature	Maximum fan 2 inlet temperature	max. 40 °C (+ 10 °C temperature lift of fan 2)
Control valve 1	Compressor inlet pressure based on mass in the primary HTHP loop	Minimal pressure of vacuum pump	min. 0.25 bar(g)
Control valve 2		Maximum pressure after the compressor	max. 7 bar(g)

Industrial process integration of the Brayton HTHP

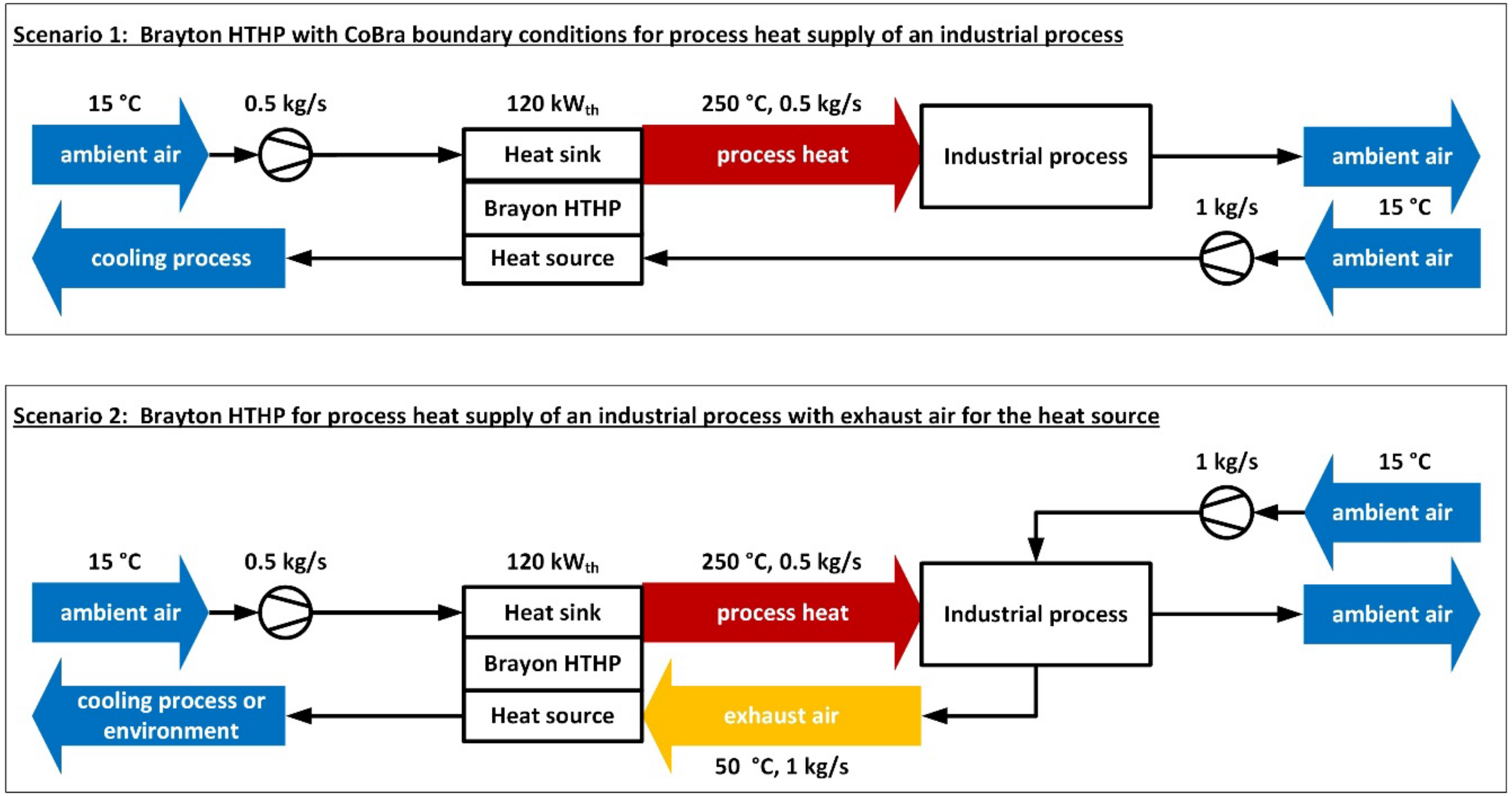


Figure: Scheme of the recuperated simulation model with design parameter (black dotted line) and controllable components (red line)

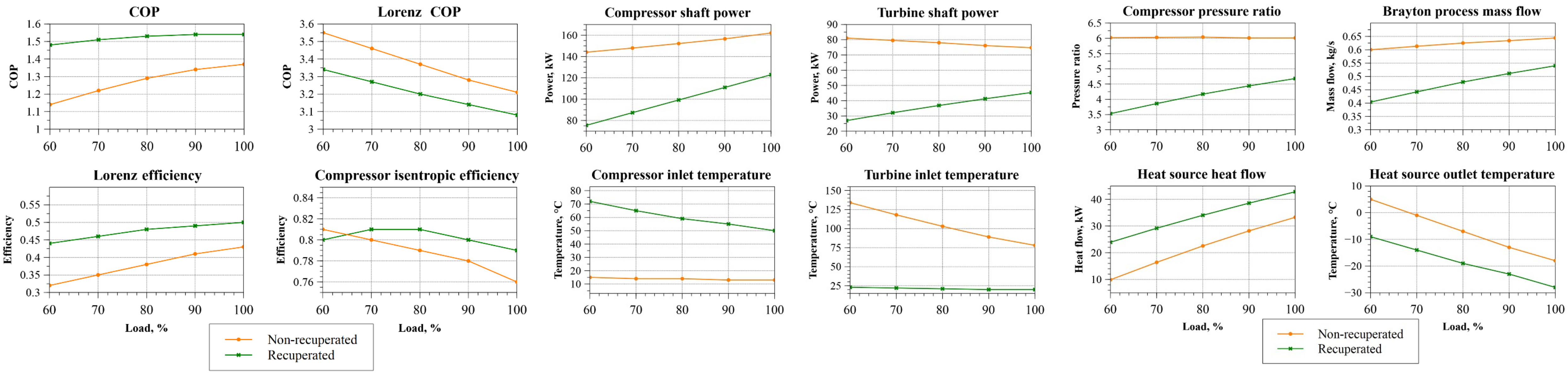
Results

Range of industrial process conditions for the part load operations

Investigation Scenario	unit	Scenario 1		Scenario 2	
Load	%	100	60	100	60
Heating capacity	kW_{th}	120	72	120	72
Heat sink inlet temperature	°C	15	15	15	15
Heat sink mass flow rate	kg/s	0.5	0.3	0.5	0.3
Heat source heat capacity	kW_{th}	-	-	40	20
Heat source inlet temperature	°C	15	15	50	50
Heat source mass flow rate	kg/s	1	1	1	1

Results

Results of the Brayton HTHP - Scenario 1



Results

Results of the Brayton HTHP - Scenario 2