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

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Abstract

Electrification of industrial process heat from renewable sources can contribute to the reduction of energy-related CO2 emissions. High-temperature heat pumps are one of the most important technologies to realize this electrification while reducing the electrical energy required for it. The Institute of Low-Carbon Industrial Processes of the German Aerospace Center (DLR) is developing high-temperature heat pumps (HTHP) based on reverse Brayton and Rankine cycles for heat transfer temperatures above 150 °C. The development and integration process of HTHPs for industrial processes often starts with their sizing at nominal operating conditions. Once the operational boundary conditions are defined, the individual components are sized. A large proportion of industrial heat pumps operate at a fixed point and are not optimized or designed for frequent part-load operation. This is expected to change, especially when heat pumps are required for industrial processes with part load operation. The current work presents an analysis of the part load operation of a reverse Brayton HTHP built in the laboratory of DLR and investigates its operational limits.

Keywords: high temperature heat pumps; reverse Brayton cycle; process heat; stationary process simulation

1. Introduction

1.1. Motivation

Reducing greenhouse gas (GHG) emissions by 2050 is one of the most important steps to achieve the European Union's (EU) climate goals [1]. An interim target for 2030 is to reduce GHG emissions by at least 55% compared to 1990 levels [2]. Industrial heating and cooling demand in the EU accounts for over 25 % of these emissions [3]. More than 30 % of the cumulative energy demand for heating and cooling is used for industrial processes. This heating and cooling demand is mainly met by fossil fuels and a transformation to a GHG-free energy system is required to achieve the EU climate goals [4]. Several studies have been carried out in the past to estimate the heat demand for different process temperatures and industrial sectors in the EU. Naegler et al. [5] and Rehfeldt et al. [6] analysed several industrial processes and concluded that there is a large demand for heat at temperature levels from 100 °C to 500 °C mainly in industrial sectors such as chemical, paper and food industry. It is shown that the total final energy demand for heat in the EU-28 Member States in 2012 was 8518 PJ. The resulting total energy demand for heat at process heat temperature levels of 100 - 400 °C is 2214 PJ and above 400 °C 3859 PJ [5]. Marina et al. [7] identified the potential of heat pumps with heat sink temperatures up to 200 °C and analyzed their application in the food, paper, chemical and refinery sectors. They highlighted that a total of 641 PJ/year of process waste heat could be covered by industrial heat pumps. Wolf [8] investigated the application potential for heat use in German industry. He found a technical potential of 611 PJ using heat pumps with a maximum heat sink temperature of 140 °C. Kosmadakis [9] analyzed the possibilities of waste heat recovery using industrial heat pumps. He concluded that industrial heat pumps in the EU have a total potential of 28.37 TWh/year (102.132 PJ).

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All authors also emphasized that high-temperature heat pumps (HTHP) driven by renewable energy can make a significant contribution to the decarbonization of industrial heat supply in Europe and also significantly reduce the necessary primary energy demand for industrial heating [10], [11].

Nomenclature

Abbreviations		*Variables*	
3WV	Three-way-valve	COP	Coefficient of performance
CoBra	Cottbus Brayton cycle heat pump	COP_{Lorenz}	Lorenz COP
DLR	German Aerospace Center	P_c	Mechanical power of compressor, kW
EU	European Union	P_T	Mechanical power of turbine, kW
GHG	greenhouse gas	$\dot{Q}_{in}$	Heat sink heat flow of LTHX, kW
HP	heat pump	$\dot{Q}_{int}$	Internal heat flow of IHX, kW
HTHP	high-temperature heat pump	$\dot{Q}_{out}$	Heat source heat flow of HTHX, kW
HTHX	high-temperature heat exchanger	T	Temperature, K
IHX	Recuperator (internal heat exchanger)	T_m	Logarithmic mean temperatures, K
LTHX	low-temperature heat exchanger	η_{Lorenz}	Lorenz efficiency
TRL	Technology Readiness Level		

1.2. Short overview of the state of the art on HTHPs

The literature provides a first overview of the state of the art. For example, Wolf et al. [12] compared available types and technologies of heat pumps (HP), focusing on compression, absorption and hybrid HPs with a temperature delivery limit of 120 °C. Schlosser [13] investigated the decarbonization of industrial heat supply through the integration of heat pumps and presents methods for techno-economic detailed planning. Arpagaus et al. [14] give an overview of HPs already available on the market and the state of the art.

The IEA HPT Annex 58 project is currently underway to provide an overview of the state of the art and ongoing developments for HTHP systems and components [15]. This overview of the development of supplier technologies for HTHP shows that maximum supply heat sink temperatures between 115 °C and 280 °C with heating capacities up to 70 MW are available at the highest Technology Readiness Level (TRL) of 9 [15]. In addition, the demonstration cases of different technologies for HTHP have heat sink temperatures up to 211 °C, heating capacities up to 12 MW, and a coefficient of performance (COP) of 5.3 maximum [15].

In addition, published work with a simulative background has focused on the on-design operation of HTHPs and their techno-economic evaluation. For example Zühlsdorf et al. [11] presented possible solutions for a HTHP with sink temperatures around 250 °C and recommended a closed-loop reverse Brayton or Rankine cycle. Oehler et al. [16] investigated the part load capability of a HTHP based on a closed loop reverse Brayton cycle. They presented a combined method to operate such heat pumps at part load either by changing the speed of their compressor or by actively controlling the working fluid mass in the closed loop of the heat pump. As part of investigations on the load strategy of a gas turbine using the Brayton cycle, the benefits of fluid inventory control were also investigated by Pradeep Kumar et al. [17]. Both studies have shown that a Brayton cycle based HP can achieve high efficiencies and provide good flexibility by using an appropriate part load strategy [16], [17].

1.3. Motivation and contributions of this study

Potential applications for Brayton heat pumps are drying processes, e.g. in the food industry with temperature requirements up to 280 °C [11], [18]. Another application is preheating processes, for example in the metal industry [11] In some cases, variations in production conditions (temporary production line shutdowns, etc.) often lead to variations in the mass flow rate of the heating medium, even though the same product is being processed. To accomplish this task, it is necessary to understand the operating behavior, especially at partial load.

The DLR Institute of Low-Carbon Industrial Processes is developing a HTHP pilot plant based on the Reverse Brayton Cycle to analyze the feasibility of heat sink temperatures up to 300 °C. The aim of the present work is to analyze the steady-state part-load performance of this Reverse Brayton Cycle pilot plant under different boundary conditions. The ability and limitations of part load operation play an important role in the integration of HTHP into existing industrial processes with different operating conditions. The conclusions of this work are expected to pave the way for further investigations on the part load operation of HTHP.

2. Research object

This work focuses on the part load operation for reverse Brayton high-temperature heat pumps in the context of industrial process integration. The following subsections outline the research object of this considerations. First, the reverse Brayton process and the main evaluation parameters are described. The technical basis for the simulations and a detailed description of a prototype are then presented.

2.1. Brayton process and coefficient of performance

The reverse Brayton process considered in this study is shown in Figure 1. By absorbing mechanical power from the compressor shaft (P_c), the compressor (C) raises pressure and temperature of the working fluid (1 → 2). After that, 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 latter (P_T) is used directly to partially drive the compressor. In the DLR design, the turbine and the compressor are mechanically decoupled and the exchange of energy takes place through a power electronics system. 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.

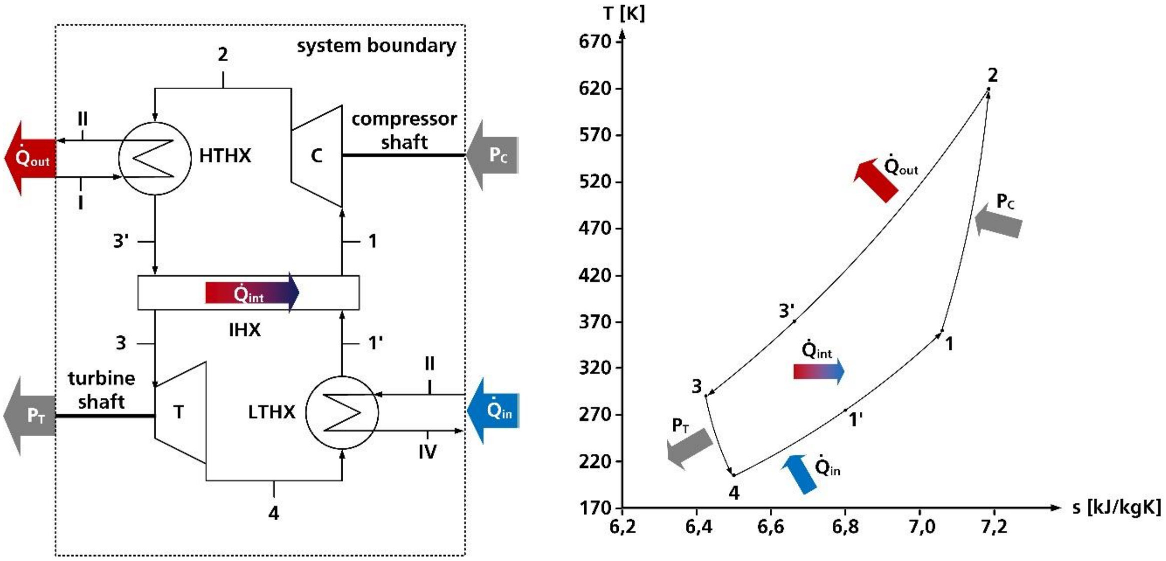

Figure 1. Scheme of the recuperated Brayton process (left) and sketched T-s-diagram of the simulation model of the CoBra

With regard to the following investigations, process parameters of heat sink, heat source, heat flow, temperature, and drive power outside the system boundaries of the Brayton process - see Figure 1- are mainly evaluated. In addition, the investigations on the heat pump system also need a main indicator to evaluate the results of the different part load operations. Arpagaus et al. [19] described the key efficiency indicator of a heat pump as the coefficient of performance (COP). The COP is defined as the ratio between the output heat power and the applied drive power. Considering the application of the Brayton process shown in Figure 1, the COP (Equation 1) is defined in these considerations as the ratio between the transferred heat flow $\dot{Q}_{out}$ and the difference between the drive power at the compressor shaft P_C and output power of the turbine P_T.

$$COP = \frac{\dot{Q}_{out}}{P_C - P_T} \tag{1}$$

Arpagaus et al. [19] and Marina et al. [7] described, that operating between process and waste heat streams with constant heat capacities and varying temperatures (temperature glides), the maximum theoretical COP is known as the Lorenz COP. Considering the application of the Brayton process shown in Figure 1, the Lorenz-COP (Equation 2) is defined as the ratio between the logarithmic mean temperatures T_m at the HTHX (Equation 3) and the LTHX (Equation 4). The Lorenz efficiency will not be reached in practice due to all kind of losses. To determine the real COP, a system efficiency must be considered [19]. An efficiency term, which relates the actual COP to the maximum Lorenz COP is given in Equation 5.

$$COP_{Lorenz} = \frac{T_{m,HTHX}}{(T_{m,HTHX} - T_{m,LTHX})} \tag{2}$$

$$T_{m,HTHX} = \frac{T_I - T_{II}}{\ln(T_I/T_{II})} \tag{3}$$

$$T_{m,LTHX} = \frac{T_{III} - T_{IV}}{\ln(T_{III}/T_{IV})} \tag{4}$$

$$\eta_{Lorenz} = \frac{COP}{COP_{Lorenz}} \tag{5}$$

2.2. DLR-HTHP Prototype CoBra

At the DLR Institute of Low-Carbon Industrial Processes, a prototype of a high-temperature heat pump based on the reverse, closed-loop and recuperated Brayton cycle was developed and built. The prototype is called CoBra (**Co**ttbus **Bra**yton). The main components are the two turbo machines and three shell-and-tube heat exchangers. To accommodate a large number of possible experimental investigations, the following design features are included:

- 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

In addition to the design features of the prototype CoBra, the plant has been equipped with a comprehensive range of instrumentation to monitor the operation of all components in detail. Each circuit - the Brayton primary and the two secondary circuits - has a mass flow meter (MFM) and the necessary temperature and pressure measurements to evaluate the performance of the system under all operating conditions.

3. Methodology

A simulation model of the Brayton HTHP based on the CoBra has been developed in order to study the part-load operation in the context of industrial process integration and as a function of different process conditions. Furthermore, it is necessary to consider the possible industrial process integration of the Brayton HTHP. The following subsections outline the simulation model used for the numerical study and set up different Scenarios for the integration of the Brayton HTHP.

3.1. Simulation model of the Brayton HTHP

The first part of the development process of an industrial heat pump requires a design of the system based on defined boundary conditions. A simplified thermodynamic model of a reverse, recuperated Brayton cycle has been implemented in the software tool EBSILON® Professional [20]. This model considers the detailed operating maps of each component and is capable of simulating part-load operation of the entire cycle for steady-state operating conditions. The additional features of the off-design model can be summarized as follows:

- 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

The simulation model derived by the Brayton HTHP is based on parameters and maps of the main components and design features of the CoBra (see subsection 2.2). Environment conditions used for the first approach of the design was dry air as working fluid, the inlet temperatures of the HTHX and LTHX is set equal to 15 °C and the heat sink outlet temperature equal or higher than 250 °C. Based on this boundary conditions, Figure 2 shows the process design parameter of the fully recuperated CoBra at the maximum compressor speed of 105 000 min^{-1}. In general, the allowable range of tests is based on the operating limits of the plant. (see Table 1). The resulting model is conditionally switchable, allowing investigations of the Brayton heat pump in the context of industrial process integration and as a function of different process conditions.

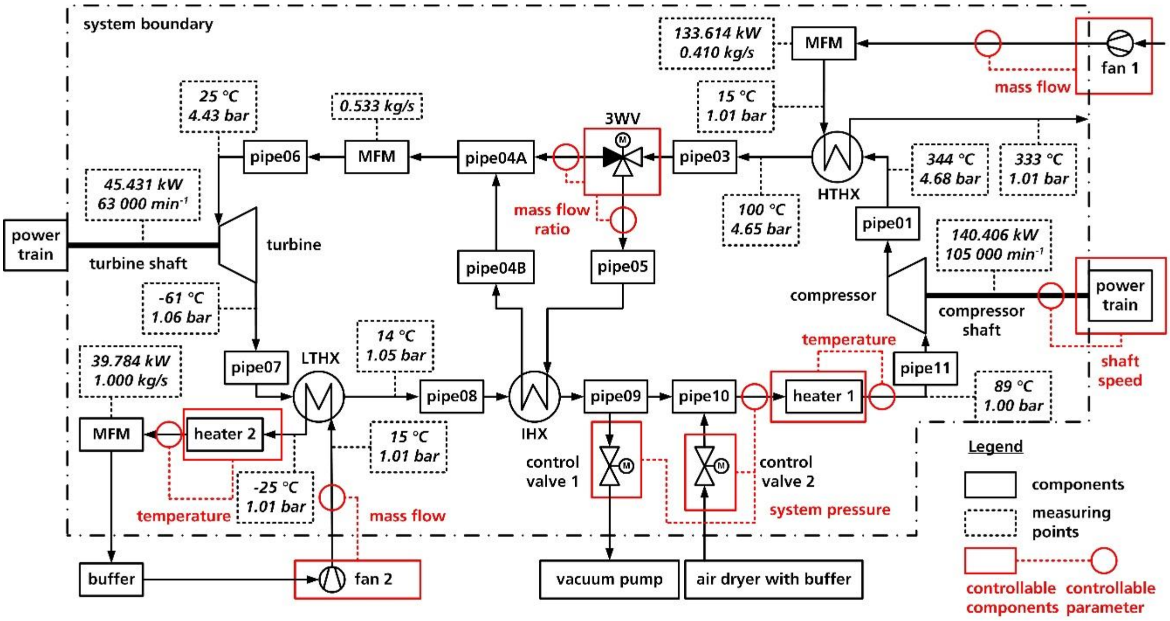

Figure 2. Scheme of the recuperated simulation model with design parameter (black dotted line) and controllable components (red line)

Table 1. 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)

3.2. Industrial process integration of the Brayton HTHP

In order to investigate the integration of the Brayton HTHP into an industrial process, it is necessary to define an appropriate integration Scenario. In the current work, a generic industrial process is assumed that requires a flow of hot air with a fixed temperature of 250°C and a mass flow of 0.5 kg/s (heat flow of 120 kW$_{th}$). In addition, it is assumed that this industrial process returns an exhaust air heat flow with a temperature of 50 °C at a mass flow of 1 kg/s (based on the heat mass flow rate of the CoBra). In general, the output temperature of the heat source is considered as a free parameter. Depending on its temperature, this flow can be made available for a cooling process or can be discharged to the environment. Finally, Figure 3 shows the two integration Scenarios. The first considers a Brayton HTHP with CoBra boundary conditions. The second introduces a recirculation of the exhaust air heat flow for the heat source of the Brayton HTHP.

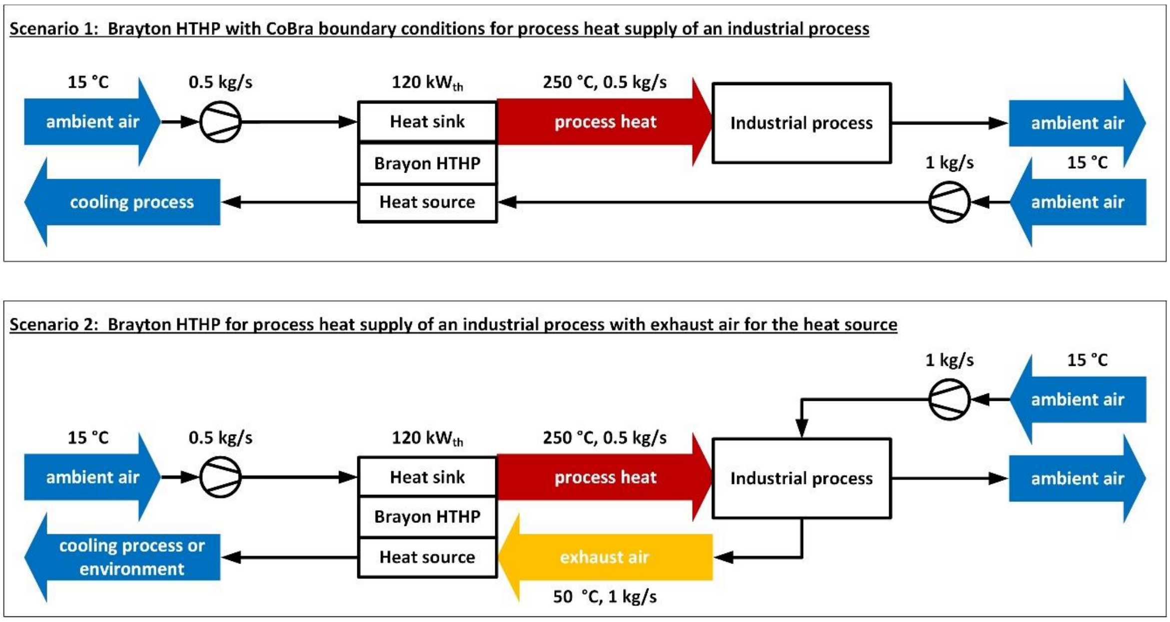

Figure 3. Schemes of process integrations Scenarios of a Brayton HTHP into an industrial process

4. Results and discussion

Table 2 shows the operating range that used to study the off-design operation of the HTHP. It should be noted that, based on the compressor map, the minimum possible load is equal to approximately 60 % due to the compressor surge limit. In general, the heat sink outlet temperature is specified fixed at 250 °C. The heat source outlet temperature is considered as a free parameter that can potentially be made available for a cooling process.

Table 2. 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

For the described integration Scenarios (see Figure 3), the results are presented in the following subsection. The HTHP load has been varied between 60 – 100 % (fan 1 as control parameter, mass flows see in Table 2) and the operating modes with and without recuperation have been studied. The degree of recuperation (3WV as control parameter, 0 % is non-recuperated, 100 % is recuperated) and the speed of the compressor (free parameter between 80 000 and 105 000 rpm) are the only variable control parameters. The other control parameters are fixed (fan 2 is 1 kg/s, heaters 1 and 2 with no heat input, control valves 1 and 2 are deactivated for no fluid inventory control).

4.1. Results of the Scenario 1

Figure 4 shows the compressor efficiency for the part load operations of Scenario 1. The comparison shows that the recuperated HTHP generally has a higher COP and Lorenz efficiency in all part load modes. The reason for the higher HTHP efficiency can be explained by the compressor and turbine mechanical powers conditions, inlet temperatures and compressor pressure ratio (Figure 5).

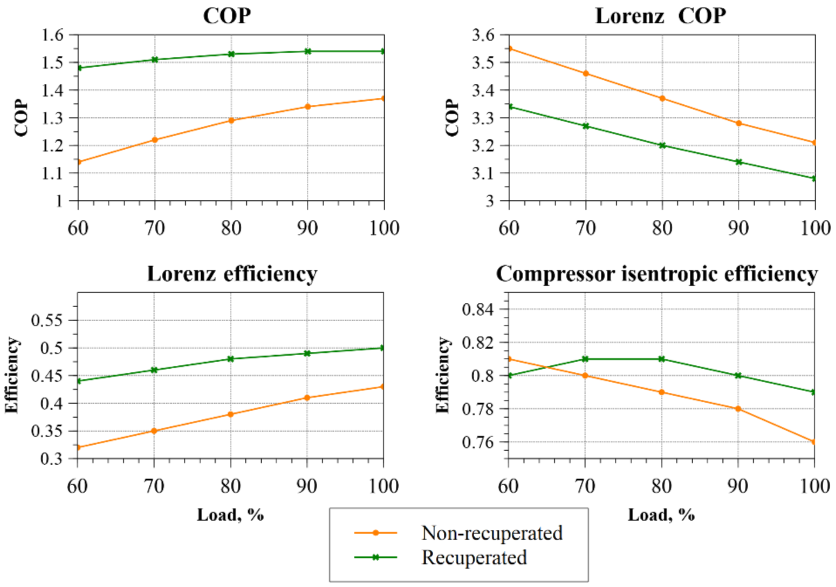

Figure 4. Process parameter of the Brayton HTHP (Part 1) - Scenario 1

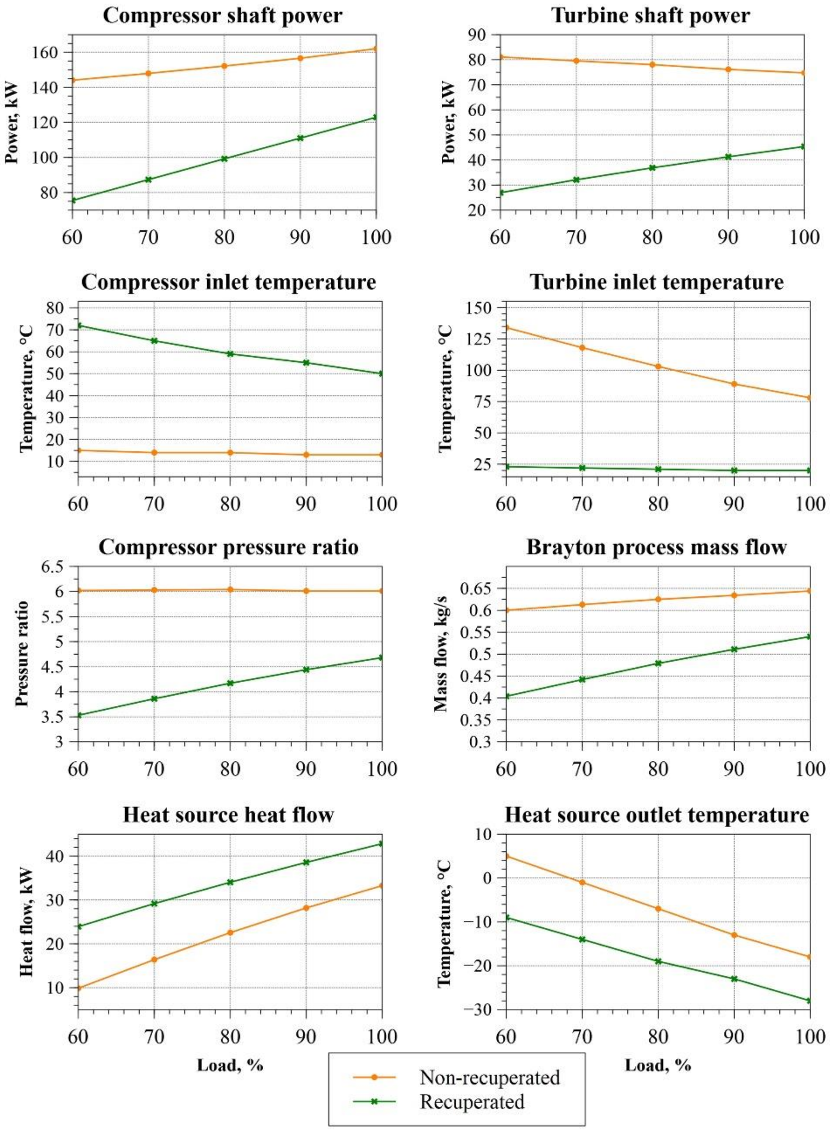

Figure 5. Process parameter of the Brayton HTHP (Part 2) - Scenario 1

Figure 5 shows that the recuperated operation mode has a significantly lower compressor power at all part load conditions, which is not compensated by the lower turbine power. Relative to the constant heat flow through the heat sink, this effect results in a higher COP (see equation 1 in subsection 2.1). The lower compressor and turbine power is due to the internal heat transfer through the IHX, which generally results in higher compressor inlet temperatures and lower turbine inlet temperatures. This is due to the fact that the only controllable parameter to run at part load is the compressor speed, which is controlled for an appropriate pressure ratio, which in turn provides the 250°C. When the compressor shaft speed is reduced, the Brayton mass flow and the compressor pressure ratio in the primary circuit are also reduced. This effect shifts the compressor operating condition to points on its map with higher isentropic efficiencies compared to non-recuperated operation (Figure 4).

In addition, Figure 5 shows that the consistently low turbine inlet temperatures and the generally lower Brayton mass flow in the recuperated mode in turn ensure consistently very low heat sink outlet temperatures and a higher heat source heat flow. With increasing part load, the outlet temperatures increase in both operating modes, which in turn leads to higher theoretical maximum efficiencies in the form of the Lorenz COP (Figure 4).

4.2. Results of the Scenario 2

Figure 6 shows the complete process parameters of Scenario 2 and the difference between the Brayton HTHP for the part load operation of Scenario 2 compared to Scenario 1. In general, it can be seen that the higher inlet temperature at the heat source results in a higher COP and, at full load, nullifies the effects and benefits of recuperation described above. This can also be seen where the turbomachinery capacities are almost the same at full load. This effect is cancelled as the partial load increases, as the internal heat transfer increases and the conditions become more similar to those in Scenario 1. In general, the inlet temperatures at the turbomachinery are higher, which leads to better conditions (e.g. compressor pressure ratio and Brayton mass flow) and ultimately to better but more similar efficiencies - compared between operating modes - as well as higher heat source flows and outlet temperatures in Figure 6.

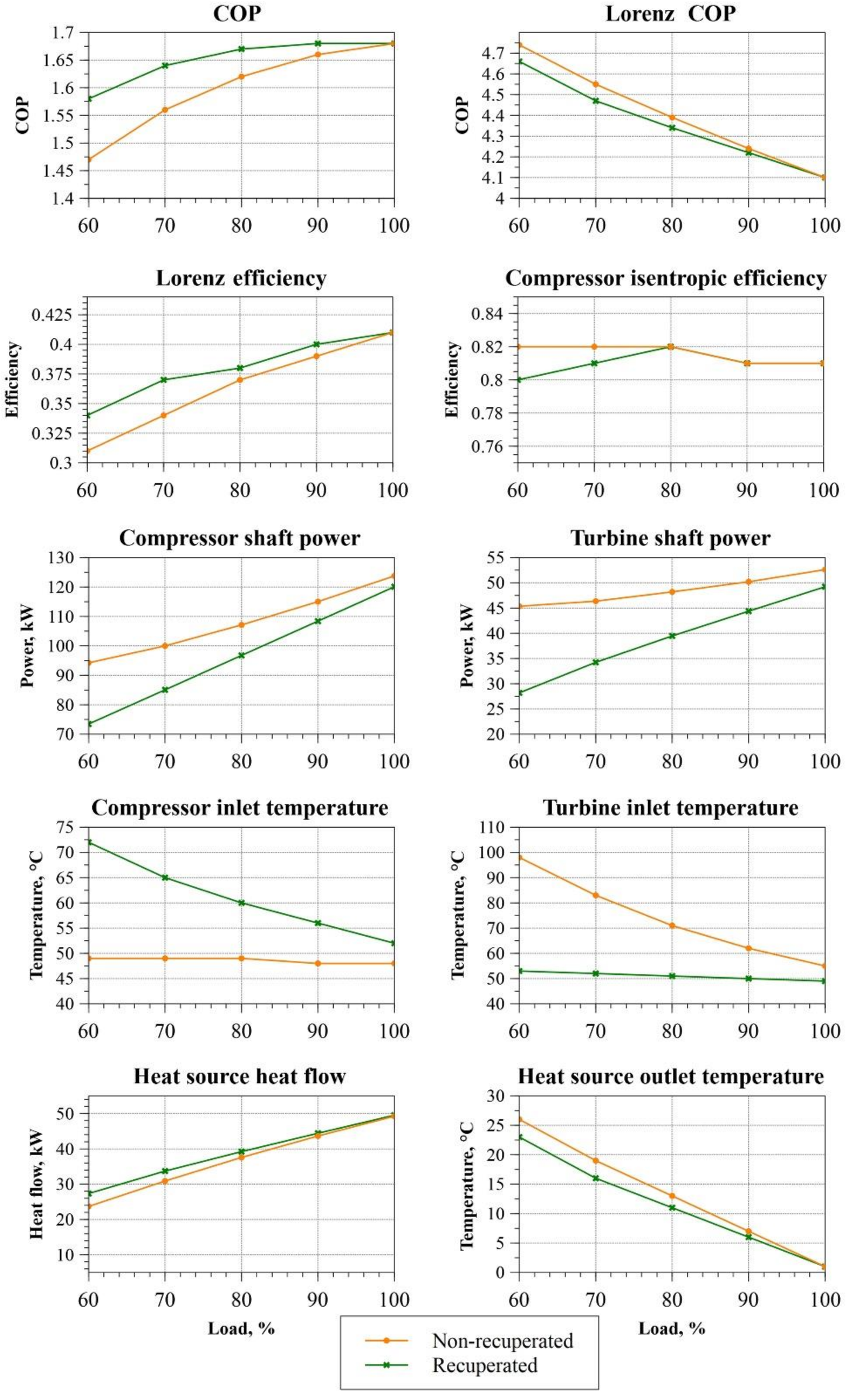

Figure 6. Process parameter of the Brayton HTHP - Scenario 2

4.3. Comparison of the two Scenarios of industrial process integration of the Brayton HTHP

Firstly, the graphs of the key efficiency indicator COP show the typical increase in COP for heat pumps as the heat source inlet temperature rises. Scenario 2 has a significantly higher efficiency than Scenario 1 at all load conditions.

In relation to the influence of recuperation, both Scenarios show that the recuperated mode has a higher COP than the non-recuperated mode in part load operation. However, Scenario 2 shows that recuperation has no effect on the heat sink and heat source conditions and the COP of the Brayton HTHP as the heat source inlet temperatures increase. From this effect it can be concluded that as the available temperature increases, the decision of whether a recuperated process is required becomes obsolete.

A consideration of the heat sink conditions indicates that the type of process integration is critical to the intended application. This is because the outlet temperatures drop significantly at lower temperatures (see Scenario 1) and the use of the Brayton HTHP only makes sense if the cold temperatures are used in a cooling process.

Finally, a look at the controllable parameter of the compressor shaft speed of the two Scenarios in Figure 7 reflects the behavior of the heat pump in both Scenarios, where at low heat source inlet temperatures (Scenario 1) a higher demand is placed on the compressor than at increasing heat source inlet temperatures (Scenario 2), up to the approximate balance at full load due to cancellation of the positive recuperation effect.

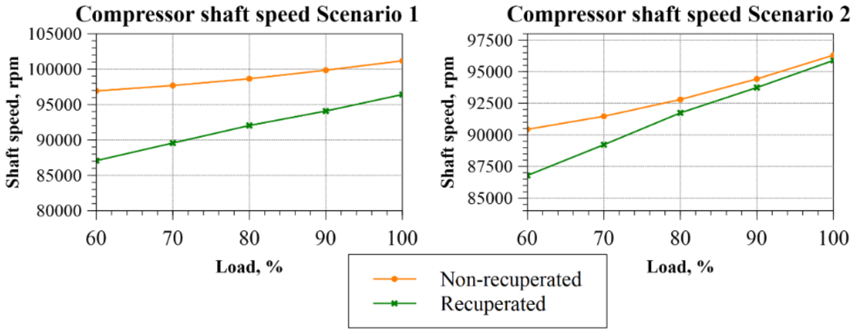

Figure 7. Compressor shaft speed of Scenario 1 (left) and compressor shaft speed of Scenario 2

5. Conclusion and outlook

High temperature heat pumps based on the reverse Brayton process can contribute to the decarbonisation of industrial drying processes. For process integration into existing industrial processes with variable conditions, the ability and limitations to operate at part load play an important role. A simulation model based on a DLR-HTHP prototype was developed in these investigations and integrated into the simulation environment of EBSILON® Professional for off-design simulation considerations. An industrial process was then assumed and described which provided two investigation Scenarios for the Brayton HTHP integration and the part load study. These investigations were initially carried out with the two controllable components, the compressor to vary the compressor shaft speed and the 3-way valve to vary the recuperation rate.

The part load studies show that the conditions of the heat source and ultimately the nature of the industrial process are critical. If efficiencies increase as expected at low inlet temperatures and increasing recuperation, the advantage of recuperation is cancelled out as inlet temperatures increase.

Based on the controllable components presented in the methodology of this research, further studies on partial load operation can be carried out with DLR-HTHP prototype CoBra. Examples include fluid inventory control, or investigating further process architectures with the electric heater upstream of the compressor to simulate an additional waste heat application.

Furthermore, in the context of process integration, it should be noted that an experimentally designed HTHP has been studied in the context of these considerations. Although this will allow future experimental verification of the results with the DLR-HTHP prototype CoBra test facility, a potential Brayton HTHP integrated into an industrial process must be optimized for the industrial process with variable part-load conditions already in the design phase. The above considerations can serve as a basis for this.

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