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Thermodynamic analysis of an industrial process integration of a reversed Brayton high-temperature heat pump: A case study of an industrial food process

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Abstract. Industry, as a major emitter of CO_2 in the process heat sector in Europe, needs to switch from fossil fuels to renewable energy for heat supply. High temperature heat pumps (HTHP) can electrify process heat and integrate renewable electricity into industrial processes. The Institute of Low-Carbon Industrial Processes of the German Aerospace Center (DLR) is developing HTHPs based on the reversed Brayton and Rankine cycles for delivery temperatures above 150°C and is investigating the industrial process integration of this novel technology. The current study considers different integration strategies of a reversed Brayton HTHP in a food production process with a heat sink at 250 °C. A thermodynamic analysis evaluates the results. This study allows conclusions to be drawn about the process integration of Brayton HTHPs in industrial food processes or other industrial processes with heat sinks around 250 °C.

1 Introduction

In 2022, global greenhouse gas (GHG) emissions from energy combustion and industrial processes rose to a new all-time high of 36.8 gigatonnes (Gt), 9.2 Gt (25%) alone from the industrial sector [1]. The European Union (EU) has set targets to reduce GHG emissions by 55% from 1990 levels by 2030 and to achieve CO_2 neutrality by 2050 [2]. Fossil energy is the dominant energy carrier for heating and cooling in the EU industrial sector, accounting for the half of total final energy demand. This heat is consumed at different temperature levels, depending on the industrial branch [3]. Rehfeldt et al. [4] studied processes in the European industrial sector and found that the paper, food and chemical industries in particular have process heat requirements in the range of 100°C to 500°C. Previous research shows high potential for integration of HTHP in this temperature range [5–7]. Arpagaus et al. [8] provides an overview of HTHPs already 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 [9].

This study addresses two methods to connect a HTHP into an existing industrial process quickly and efficiently. A first approach is shown in the context of a preliminary design planning, comparing two different possibilities for process integration at the heat sink of a recuperated Brayton HTHP to provide dry air around 250 °C.

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2 Methodology

In order to study the process integration of the Brayton HTHP into the industrial process, it is necessary to define an integration scenario. In the current work, an industrial food process is assumed that needs a dry air heat flow of 500 kW_{th}. The temperature at the process heat exchanger (Process HX) is assumed to be the temperature rise of 40 K (210 up to 250 °C) and the mass flow resulting from the assumed heat flow and air specifications. Two different heat sink process integrations of the Brayton HTHP are evaluated. The first process is integrated into a thermal oil circuit and the second process is integrated directly into the process heat exchanger.

The industrial food process generates a waste heat stream at a temperature of 90°C that is recovered with water. In addition, for the purpose of the studies, the waste heat recovery (WHR) system can be subjected to fluctuations of down to 50°C and is complemented by an additional solar thermal system, so that the temperature of the waste heat source can be increased to 150°C. The resulting temperature range of the heat sink is 50 up to 150 °C.

The Brayton HTHP under consideration is based on a typical reversed and recuperated Brayton cycle. Powered by a direct electrical drive, the compressor raises pressure and temperature of the dry air as working fluid. A high temperature heat exchanger (HTHX) transfers sensible heat to the heat sink and cools down the working fluid. An internal heat exchanger (IHX) or Recuperator transfers some of the hot residual heat to the working fluid (air) in front of the compressor and reducing the temperature of the working fluid before it expands through a turbine. The mechanical output of the turbine, which has the same shaft as the compressor, is used directly or with transmission to partially drive the compressor. After expansion, the working fluid pressure drops to the initial level while its temperature decreases. At the heat source, the working fluid absorbs heat in the low temperature heat exchanger (LTHX) and then leaves the internal heat transfer of the IHX to complete the cycle.

Fig. 1 shows the flow chart of the two cases heat sink process integration of the recuperated Brayton HTHP.

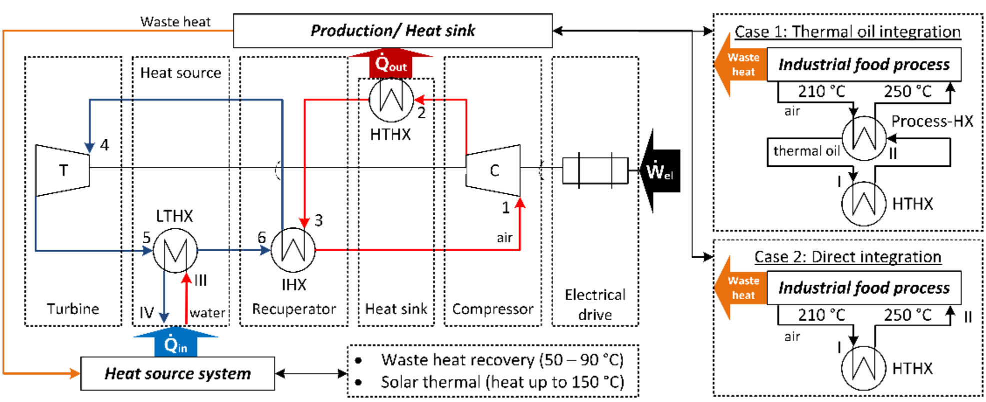

Fig. 1: Flow chart of the two cases heat sink process integration of the Brayton HTHP

The cycle simulations were carried out using the EBSILON® Professional (EBSILON) [10] flow chart simulation software. EBSILON takes the described input values and process concepts and calculates the corresponding mass flows, temperatures and pressures at each state using the first and second laws of thermodynamics. EBSILON is characterized by the universality of the approach and the convergence reliability of the algorithm solution [10]. This allows to show thermodynamic parameters to evaluate the thermodynamic.

To evaluate the effectiveness, the heating power related Coefficient of performance COP_H (Eq. 1) is used as the ratio between the transferred heat flow of the heat sink to the process $\dot{Q}_{out}$ and the electrical drive power $\dot{W}_{el}$ [11]. Due to the temperature glide between the heat source $T_{m,source}$ and heat sink $T_{m,sink}$, the theoretical maximal efficiency COP_{Lorenz} (Eq. 2) is still calculated as well as the Lorenz efficiency η_{Lorenz} as the ratio of COP_H to COP_{Lorenz} [6].

$$COP_H = \frac{\dot{Q}_{out}}{\dot{W}_{el}} \quad (1)$$

$$COP_{Lorenz} = \frac{T_{m,sink}}{(T_{m,sink} - T_{m,source})} \quad (2)$$

$$T_m = \frac{T_{in} - T_{out}}{\ln(\frac{T_{in}}{T_{out}})} \quad (3)$$

3 Results

The two cases for the connection of the heat pump to the process are shown in Fig. 1 and have been modelled in EBSILON in a simplified way in order to carry out a first design and an exergy analysis. These first considerations are based on the base load, which both cases are being operated with the WHR only (input temperature of 90 °C, without additional heat up by the solar thermal). Additionally, the effectiveness of both designs is evaluated, based on a gradual temperature rise of the heat pump from the heat source to the heat sink, triggered by the additional load of the solar thermal (heat up to 150 °C).

In order to find the main component design values of the Brayton HTHP, the literature-based modelling assumptions for the direct power-driven turbomachinery are 75% isentropic efficiency for both compressor and turbine, and 95% efficiency for the direct electrical drive. In addition, the minimum temperature differences of 7.5 K for liquid/gas and 10 K for gas/gas heat exchangers are applied [12]. Pressure and heat losses were disregarded.

Table 1 shows the main component design values of the two cases of the process integration based on the above modelling assumptions and a parameter optimization in EBSILON with WHR in base load operation. The resulting parameters of the heat exchange surfaces of all heat exchanger A_i (i = HTHX, LTHX, IHX, Process HX) and the corrected mass flow of the turbines $\dot{m}_{T,corr}$ is then determined for further investigation in EBSILON.

Table 1: Component design values of the two cases of the process integration

Component value	A_{HTHX}	A_{LTHX}	A_{IHX}	$A_{Process\ HX}$	$\dot{m}_{Turbine,corr}$
Unit	m²	m²	m²	m²	kg/s
Case 1 - Thermal oil integration	180	140	1570	420	2.495
Case 2 - Direct integration	330	130	1250	-	2.230

Fig. 2 and Table 2 show the results in exergy flow diagrams and the most important base load process parameter of both cases of the process integration. To evaluate the effectiveness of the two cases, a further parameter study with a temperature increase from 100 to 200 K is presented in Fig. **3**. This temperature lift represents the inlet temperature at the heat sink from 50 up to 150 °C with a temperature difference of 20 K (input temperature to outlet temperature) in all operation points.

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Fig. 2: Exergy analysis of the thermal oil integration (above) and direct integration (below)

Table 2 : Process parameter at base load

Parameter	Unit	Case 1	Case 2
$\dot{Q}_{out}$	kW	500.000	500.000
$\dot{W}_{el}$	kW	376.372	368.696
π_C	-	1.869	1.982
$\dot{m}_{Brayton}$	kg/s	4.084	3.872
T_I	K	510.65	483.15
T_{II}	K	530.65	523.15
T_{III}	K	363.15	363.15
T_{IV}	K	343.15	343.15
$T_{m,sink}$	K	520.59	502.88
$T_{m,source}$	K	353.06	353.06
COP_H	-	1.33	1.36
COP_{Lorenz}	-	3.11	3.36
η_{Lorenz}	-	0.43	0.40

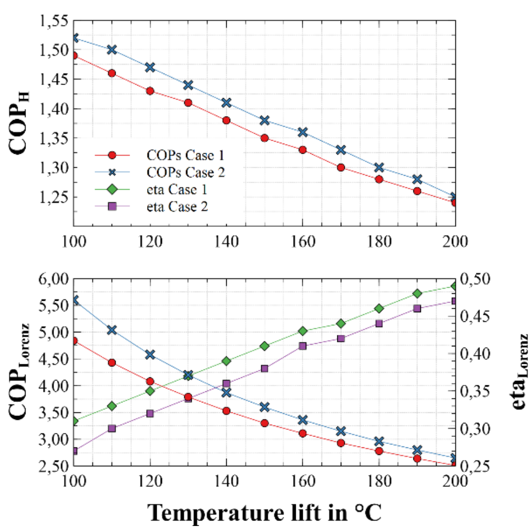

Fig. 3: Effectiveness at temperature lift

4 Discussion

In addition to analyzing potential sources of waste heat, one of the first questions when connecting a HTHP into an existing industrial process is how to integrate the heat pump. Complementary connecting into the existing process as an additional heat generator next to the existing conventional heat generator, often based on natural gas, is contrasted with substitution of the conventional heat generator. These two cases were considered above. Taking into account the assumptions made in the literature for the design of the main components, it is noticeable that the gas/gas HX have very large exchange areas. In addition, it is necessary to check whether the turbomachinery can achieve higher efficiencies in the power range studied, which would directly lead to a better efficiency of the HTHP. These facts have to be considered and evaluated in a subsequent detailed design planning.

The thermodynamic analysis in Fig. 2 shows no anomalies and the direct integration is slightly more efficient overall due to the lower temperature level at the HTHP heat sink. This is maintained even as the heat source power increases (see Fig. 3). Only the COP_{Lorenz} and η_{Lorenz} converge as the temperature increases (also see Fig. 3).

In conclusion, the question of the best process integration does not depend on the efficiency of the heat pump in relation to the existing plant integration possibilities. The disadvantage of the lower efficiency and the additional heat exchanger is offset by the advantage of the additional integration of the HTHP as a heat generator in the industrial process. This allows redundancy of two heat generators (hybrid system) and lowers the threshold for integrating a heat pump as a new technology.

5 Conclusion

High-temperature heat pumps can contribute to decarbonizing industrial processes. However, process integration of the HTHP for rapid substitution of conventional and fossil heat generators requires a costly and time-consuming design and planning phase. In this respect, the integration of the HTHP as an additional heat generator to the conventional heat generator was investigated in the previous study.

Two different heat sink process integrations of a Brayton HTHP were presented for investigation. The first process integration into a thermal oil circuit allows subsequent integration into the existing process with conventional heat generators (e.g. gas boilers). The second process integration takes place directly at the process heat exchanger.

Under the given boundary conditions, the thermodynamic analysis confirms the expectations and shows that the direct integration is slightly more effective, but this requires a redesign of the process interface for the integration of the usually larger heat sink heat exchanger of the HTHP.

Finally, the key question in the planning process is which approach is preferred. If direct integration can be achieved, which may involve significant intervention in existing process structures, then these should be preferred. A connecting into existing process structures on the other hand is creating redundancy with two heat generators and therefore means less risk to the operation. Herebly it should be noted that the efficiency is lower and the capital cost could be higher. This issue should be addressed in further studies, where a techno-economic analysis of the process in terms of driving and operating modes as well as operating times can clarify the above question or become part of a detailed design. The present investigations can be seen as a first approach or as part of a preliminary planning and can be further developed.

Nomenclature

Abbreviations		*Variables*	
DLR	German Aerospace Center	A	heat exchange surfaces, m²
EU	European Union	COP_H	Coefficient of performance
EBSILON	EBSILON® Professional	COP_{Lorenz}	Lorentz COP
HTHP	High temperature heat pump	$\dot{m}_{Brayton}$	Mass flow of Brayton cycle, kg/s
HTHX	High temperature heat exchanger	$\dot{m}_{T,corr}$	turbine corrected mass flow, kg/s
HX	heat exchanger	T	Temperature, K
IHX	Internal heat exchanger	T_m	Logarithmic mean temp., K
	(Recuperator)	$\dot{W}_{el}$	electrical drive power, kW
LTHX	Low temperature heat exchanger	π_C	Pressure ratio of the compressor
WHR	Waste heat recovery	η_{Lorenz}	Lorentz efficiency

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