Heat pump-based steam generation for pharmaceutical production: First operation insights

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Abstract

At a pharmaceutical production site in Vienna, an advanced heat pump system is implemented to provide steam at 11 bar(a) / 184°C. The heat source is the central chiller system that supplies cold water for the production site. The chiller is connected to an ammonia heat pump that produces hot water for space heating at 70°C. Since space heating is only required in winter, heat is available for further use in the new heat pump system, which is a combination of a steam generating heat pump using n-butane (R600) as refrigerant and a steam compressor. The heat pump system has a nominal heating capacity of 1.7 MW and provides steam for the production process. It replaces fossil steam boilers and thus has the potential to supply CO_2 free steam for ca. 7 months a year. The heat pump system was integrated at the production site in mid-2025. This contribution provides an insight in the operation experience, such as the coefficient of performance for the most relevant operating states occurring in the first weeks of operation.

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1. Introduction

Decarbonizing industrial process heat is one of the most important fields of actions to reduce industrial CO_2 emissions. In EU27 countries, process heat amounts to about 50% of the industrial energy demand and causes ca. 75% of the industrial CO_2 emissions. A study on direct electrification of industrial process heat [1] shows, that process heat below 200°C has a share of 39% of the process heat demand, which is currently covered by fossil fuels, most commonly with natural gas boilers. In this temperature range, steam generation is a major energy consumer, as steam is the predominant energy carrier at industrial sites for process heat below 200°C. It is either used as heat transfer medium in heat exchangers making use of the condensation energy or it is used as reactant directly in the process. According to [1], 62% of the industrial fuel demand (1290 TWh) could technically be replaced by direct electrification technologies that are already available on the market. About half of the fuel demand (680 TWh) is attributed to process heat below 200°C dominated by the food, paper and chemical industry, which can be readily electrified by heat pumps and electric boilers.

IEA's World Energy Outlook 2025 [2] states that non-energy-intensive industries (food and tobacco, machinery, mining and quarrying, transportation equipment, textiles, wood harvesting and processing and construction) consume 30% of energy in industry, and account for around 80% of added value. The share of electrification in non-energy-intensive industries in the EU has only increased slightly since 2015 and is lower than in Japan or China. In the scenario, which reaches net zero emissions (NZE) by 2050, it is expected that the share of electricity in non-energy-intensive industries rises from around 40% today to over 50% by 2035. The European Clean Industrial Deal [3] has introduced a new key performance indicator dedicated to electrification and aims to increase the economy-wide electrification rate from 21.3% today to 32% in 2030.

High temperature heat pumps are well suited to electrify process heat below 200°C, they offer significant efficiency advantages over electric boilers, as they consume less electricity due to waste heat recovery. The report of Task 1 of the international collaboration project IEA HPT Annex 58 [4] shows that high temperature heat pumps are still under development showing remarkable progress in the last 15 years with more and more products and a growing number of demonstration projects.

Steam generation with heat pumps is of high relevance as these systems can be integrated in a flexible way in industrial processes replacing fossil fuel boilers. There are several options to design steam generating heat pumps. Steam can be produced directly in the condenser of the heat pump. Here, the phase change occurs on both sides of the heat exchanger: The refrigerant condenses, water evaporates, allowing the most efficient use of the available temperature levels. In an indirect system, the condenser provides pressurized hot water, which is used to evaporate water in another heat exchanger. If a flash tank is used, the condenser also supplies pressurized hot water, which is expanded in a downstream flash tank. Water partially evaporates and is fed to the process. It was shown that the most efficient system is steam production in the condenser of the heat pump. For high temperatures lifts, the combination of such a steam generating heat pump with a steam compressor (MVR = mechanical vapor recompression) is the best option, as prior investigations [5] highlight. Research [4] shows, that MVR systems are state of the art for decades and are used for heat recovery in distillation, stripping or evaporation in chemical industry, refineries and food processing.

Two of the first systems supplying steam up to 120°C and 175°C (in a two-stage system) have been developed by KOBELCO Compressors Corporation in early 2010. These heat pumps have heating capacities of 370 kW (model SGH165) resp. 660 kW (model SGH120) [6] and operate on fluorinated refrigerants. They have a flash tank for steam generation and are applied in the chemical industry for distillation of ethanol, sterilization of chemical containers and sewage sludge drying [7]. They are currently only available in Japan.

In the last years, several other steam generating heat pumps were built and integrated in industrial production sites. In 2017, Olvondo installed a Stirling heat pump [8][9] at AstraZeneca's R&D centre in Gothenborg in Sweden. It recovers waste heat from the chillers at 36°C and supplies steam with 11 bar(a) and consist of 3 units with a heating capacity of 500 kW each. Since 2024, a heat pump system by ANEO Industries [10] is in operation in an industrial drying process at Felleskjøpet Agri in Skansen in Norway. It is a combination of an ammonia heat pump producing low pressure steam with 85°C and steam compressors to reach 120°C with 1.5 MW heating capacity. The system can supply up to 5 bar steam. In 2025, GEA has installed a pentane heat pump with a screw compressor delivering 138°C steam [11][12] at the sugar production site of Tiense Suiker in Belgium. The heat source is vacuum steam at 80°C. Steam production for prawn cooking is provided by a cascaded heat pump system by Mayekawa [13] for Stella Polaris in Norway. The bottom cycle heat pump operates with ammonia, the top cycle uses pentane and produces steam at 4 bar(a). SPH Sustainable Process Heat installed a steam generating heat pump [14] at a paper production site of Felix Schöller in Germany. The heat pump consists of a bottom cycle with R515B and a top cycle with R1233zd that supplies steam at 2.2 bar(a) from a heat source with 41°C. In Northern Europe, a 12 MW steam generating heat pump by Turboden (Mitsubishi Heavy Industries MHI group) [15][16] is installed in the pulp and paper sector. The heat pump system consists of a hydrocarbon heat pump producing steam that is compressed to a pressure of 3.5 bar(a) and a temperature of 170°C.

This contribution presents the first operation insights of the AHEAD system, an advanced heat pump system generating steam at 11 bar(a) and 184°C. It is a cascaded system, combining a steam generating heat pump using n-butane (R600) as refrigerant with a mechanical vapor recompression (MVR) system based on reciprocating piston compressors to increase temperature and pressure of the steam. The AHEAD system is implemented at a production site of Takeda, a pharmaceutical company, in Vienna, Austria and it is integrated at site energy supply level replacing the natural gas steam boilers. With a heating capacity of 1.7 MW and a production of up to 2.5 t/h of steam, the AHEAD system can cover the complete steam demand of the production site. Takeda operates a central chiller system supplying cold water with 6°C for cooling purposes. The central chiller consists of three chillers with 2 MW each using ammonia as refrigerant. One chiller is connected to an ammonia heat pump valorizing the waste heat at 35°C to produce hot water for space heating at 70°C. As heating is predominantly used in winter and only to a small extent in summer, this heat pump serves as the heat source for the AHEAD system to produce steam. The AHEAD system has the potential to generate CO_2-free steam for over 7 months annually, resulting in potential savings of up to 1,600 tons of CO_2, representing an approximately 80% reduction for the production site. The AHEAD system is a versatile multi-temperature-level heat pump completing the decarbonization concept of energy supply at the production site. It is operated on natural refrigerants only. Due to integration on supply level, the system can be multiplied to many other production sites requiring cold water, heating and steam and is well suited for retrofitting existing installations.

After successful completion of test runs of the heat pump at a testing facility in spring 2025, the commissioning of the AHEAD system started in fall 2025. The system will be scientifically monitored and optimized for at least 4000 h. This contribution summarizes the design and integration of the AHEAD system and presents operation experience at a testing facility and at the production site of Takeda. It addresses the research question of whether the operation of the system at the industrial site is matching the design and operation at the testing facility, and how efficient the system is.

2. Approach and method

2.1. Design and integration of the AHEAD system

The AHEAD system consists of a steam generating heat pump and an MVR system to reach a steam pressure of 11 bar (a). The first stage, the steam generating heat pump, is designed and built by SPH Sustainable Process Heat, a German heat pump manufacturer. SPH is also responsible for the integration of the MVR system, that is sourced from the steam compressor manufacturer Spilling. As shown in Figure 1, the AHEAD system is integrated in the central heating and cooling supply of the production site.

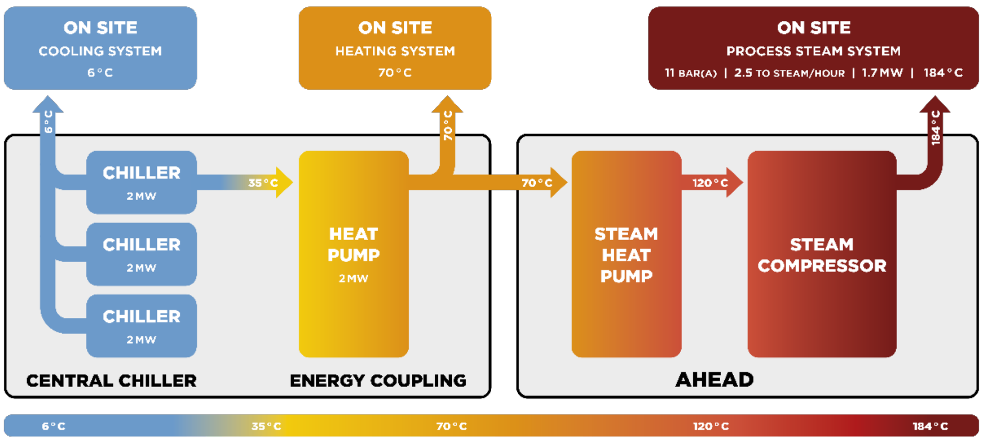

Figure 1. Integration of the AHEAD system into the existing thermal energy infrastructure at the Takeda site

For the design of the AHEAD system, several boundary conditions have important influence, as they show significant variations across the year, such as the waste heat provided by the chillers, the space heating demand and the steam demand. All these factors limit the operation of the AHEAD system at times and cause operation in part load. They are illustrated in Figure 2. The existing heat pump for space heating delivers hot water at around 70°C, especially in the cold season. As cooling water demand and therefore the residual heat coming from the central chiller increases in the warmer months from April (04.2022) until October (10.2022), there is a large potential for the production of hot water by the existing heat pump. With heating demand decreasing during that warmer period, the AHEAD system uses this temporally untapped heat potential, which would otherwise be dissipated via cooling towers, to generate decarbonized steam from hot water. Steam at 11 bar(a) is needed all year round, with slightly higher demand in the colder months.

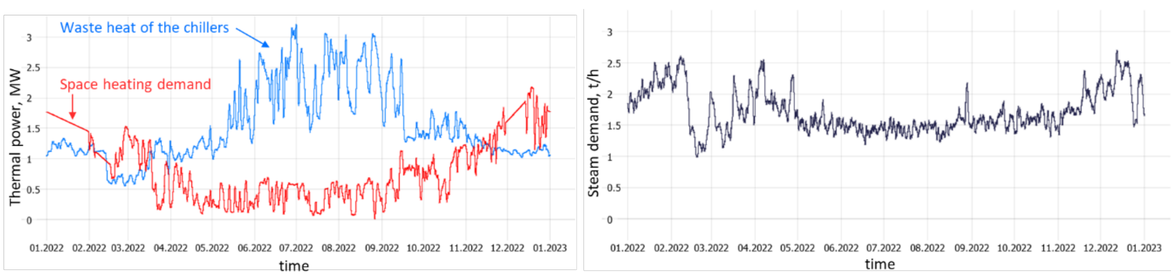

Figure 2. right: Annual demand profiles for cooling water (blue) and hot water (red), left: Annual demand profile for steam (black), [17]

To design of the AHEAD system, an annual simulation based on operation data for steam, hot water and cooling water was carried out to determine the most cost-efficient solution with regards to capital and operating costs, also aiming for maximum decarbonization by substituting steam generated with natural gas. The AHEAD configurations simulated vary in terms of the number of compressors in the heat pump and the number and size of the steam compressor units. Furthermore, operation temperatures and pressures of the heat pump and the steam compressor were varied.

The results [17] showed that the most efficient operation of the AHEAD system is achieved when the steam pressure supplied by the heat pump is minimized, specifically to 1.7 bar(a), which corresponds to the minimum inlet pressure restriction for the steam compressor. Another significant finding was that the smallest and least expensive AHEAD configuration delivers 95% of the steam output of the largest and most costly configuration, which is 1.8 times more expensive than the least expensive option [17].

Due to expected frequent operation under part load conditions, reciprocating piston compressors by Spilling were selected for the MVR. Throughout the design phase, the steam parameters changed slightly, therefore the heat pump delivers now a steam pressure of 1.9-2 bar(a), while the design pressure of the steam leaving the MVR remains at 11 bar(a). Figure 3 shows 3D models of the steam generating heat pump by SPH schematically connected to the steam compressors by Spilling.

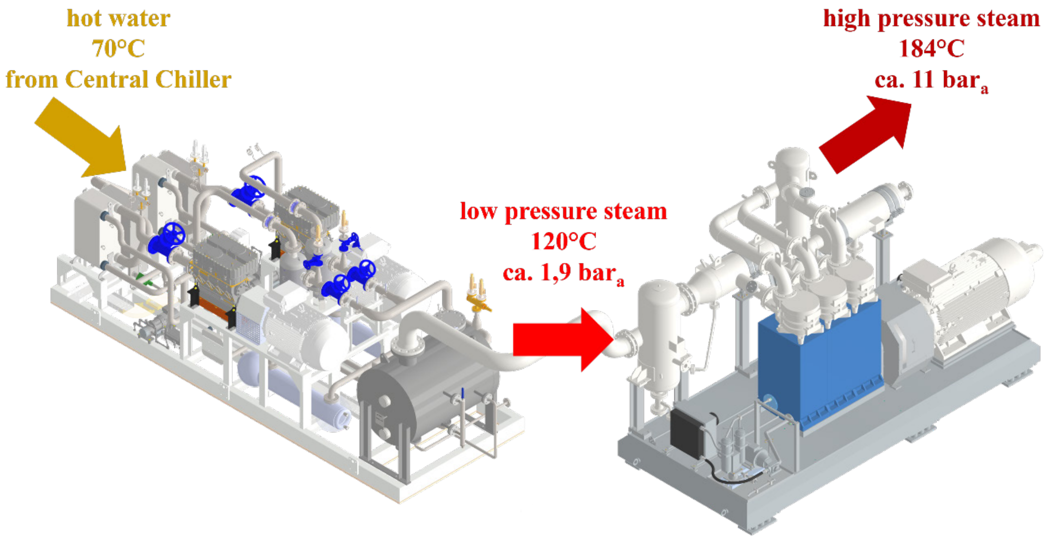

Figure 3. 3D model of the AHEAD system comprising of the steam generating heat pump (left) and the steam compressor (right), schematically connected

2.1.1. Steam generating heat pump

SPH adapted their high temperature heat pump that was designed for hydro-fluor-olefins refrigerants (HFO) for the use of n-butane (R600). The heat pump for the chosen configuration of the AHEAD system is equipped with two evaporators connected in series on the heat source side, which is illustrated in Figure 4. On the refrigerant side, the evaporated refrigerant is superheated in two recuperators (internal heat exchangers) and compressed in two compressors, one for each evaporator. After the compressors, the refrigerant streams are merged and fed into the condenser, which generates steam from feedwater on the heat sink side. The condensed refrigerant is then subcooled to preheat the feedwater. Afterwards, the refrigerant is further subcooled in the recuperators, while superheating the suction gas for each compressor on the other side, before being expanded to get evaporated by the heat source again.

The condenser is designed as a plate-and-shell heat exchanger with a nominal heating capacity of 1.25 MW to produce saturated steam at 1.9 bar(a). The compressors are reciprocating piston compressors, each driven by its own electric motor with a power output of up to 200 kW.

2.1.2. Steam compression (MVR)

The MVR unit is based on reciprocating piston compressors, with two pistons designed for first stage compression from 1.9 to 4.3 bar(a), and a single piston designed for compressing the steam further up to 11 bar(a). All three pistons are driven by a single shaft powered by an electric motor. To desuperheat the compressed steam, water is injected that is precisely heated. This increases the steam mass flow provided from the AHEAD system compared the steam generating heat pump without steam compression. The MVR system and the steam generating heat pump are coordinated and are operated simultaneously.

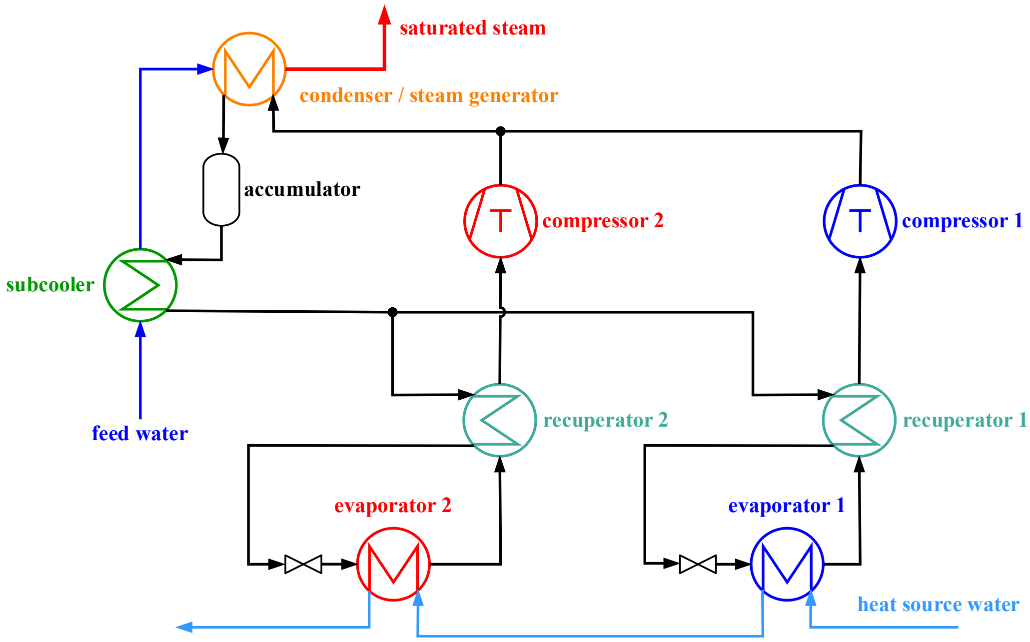

Figure 4. Refrigeration circuit of the steam generating heat pump

2.2. Measurement and calculation

For this analysis, two different data sets are used. The first data set was collected during the trial runs of the steam generating heat pump at the testing facility of SPH. These trial runs proved functionality of the heat pump and were also used to test conditions that cannot be created at Takeda to learn more about the behaviour of the heat pump and to provide data for further modelling. At the testing facility of SPH, the steam generating heat pump was operated without the steam compression system. As the electrical connection power is limited in the testing facility, the maximum possible part load factor was 66.6%.

The second data set was collected during the first operational period at the Takeda site, while the AHEAD system was still in its commissioning phase. Both the steam generating heat pump and the steam compression system were running. The steam flow meter downstream of the MVR did not function properly due to a failed pressure sensor required to convert the inductively measured volumetric flow rate into a mass flow rate, thereby precluding a comprehensive analysis of the full AHEAD system for this dataset. Thus, data analysis focusses on the steam generating heat pump only.

Table 1. Definition of steady state operation

Temperature deviation		Flow rate deviation		Compressor state deviation	
Feedwater inlet	± 1 K	Steam mass flow	± 5%	Electric power demand	± 4%
Heat source inlet		Heat source volume flow	± 10%	Speed	± 1%
Steam outlet					
Heat source outlet					
Refrigerant after the condenser	± 2 K				
Refrigerant after the accumulator					
Refrigerant before the expansion valves					
Refrigerant before compressor (suction gas)					
Refrigerant before compressor (hot gas)					

The AHEAD system, as well as the testing facility at SPH and the integration infrastructure at Takeda are equipped with numerous sensors to measure temperatures, pressures, and volume flows. Calculated values and key performance indicators are derived based on these measurements. To obtain comparable and meaningful data, an algorithm was developed to identify steady state operating points of the steam generating heat pump within the two datasets. To consider a period as steady state operation, the constraining values of the measured data must fall within a defined deviation range around the mean value for this continuous period, which was set to 5 minutes. The deviation ranges from their mean values are summarized in Table 1.

CoolProp [18] was used to calculate non-measurable fluid properties. As the steam is generated in a plate-and-shell heat exchanger [19], it is assumed that water and steam are in vapor-liquid equilibrium, thus the steam leaving the heat exchanger is saturated. Therefore, the specific enthalpy of the produced saturated steam h_{steam} is calculated assuming a vapor quality q of 1 at the heat sink outlet with its pressure p_{Steam} according to Eq. (1).

$$h_{steam} = f_{CoolProp}(p_{steam}, q = 1) \tag{1}$$

The specific enthalpy of the feed water h_{fw} as the heat sink inlet is calculated with its pressure p_{fw} and its temperature T_{fw} according to Eq. (2)

$$h_{fw} = f_{CoolProp}(p_{fw}, T_{fw}) \tag{2}$$

Therefore, the heating power of the steam generating heat pump $\dot{Q}_h$ is calculated according to Eq. (3), using the measured steam mass flow value $\dot{m}_{steam}$.

$$\dot{Q}_h = \dot{m}_{steam} * (h_{steam} - h_{fw}) \tag{3}$$

The coefficient of performance (COP) is calculated according to Eq. (4), with P_{el} being the total measured power demand for both compressors of the heat pump.

$$COP = \frac{\dot{Q}_h}{P_{el}} \tag{4}$$

The difference between the heat sink outlet temperature being the steam temperature T_{steam} and the heat source outlet temperature $T_{source,out}$ resulting in the temperature lift $T_{lift} = T_{steam} - T_{source,out}$ was chosen for calculating the COP_{Carnot} according to Eq. (5).

$$COP_{Carnot} = \frac{T_{steam}}{T_{steam} - T_{source,out}} \tag{5}$$

To calculate the second law efficiency η_{Carnot} of the heat pump system, Eq. (6) was used.

$$\eta_{Carnot} = \frac{COP}{COP_{Carnot}} \tag{6}$$

The part load factor x is defined by the actual compressor speed n_{comp} relative to the nominal compressor speed $n_{comp,nom}$ being 1500 min^{-1} according to Eq. (7).

$$x = \frac{n_{comp}}{n_{comp,nom}} \tag{7}$$

3. Results and Discussion

3.1. Results from the heat pump test runs at SPH's testing facility

For the data set at SPH's testing facility, 16 steady state operating points with at least 5 minutes duration could be derived. Figure 5 shows the log(p)-h diagram for a steady state operating point lasting about 680 min, representing a part load factor of 50%. With the heat source water inlet temperature being 74.4°C, the heat source water outlet temperature being 70.2°C and the feedwater temperature being 70.1°C, a saturated steam mass flow rate of 902.8 kg/h at 1.94 bar(a) was reached. The electric power consumption of the compressors was 136.7 kW resulting in a COP of 4.42 and a second law efficiency of 55.13%. Therefore, these mean values of operating conditions are close to the design point of the steam generating heat pump unit.

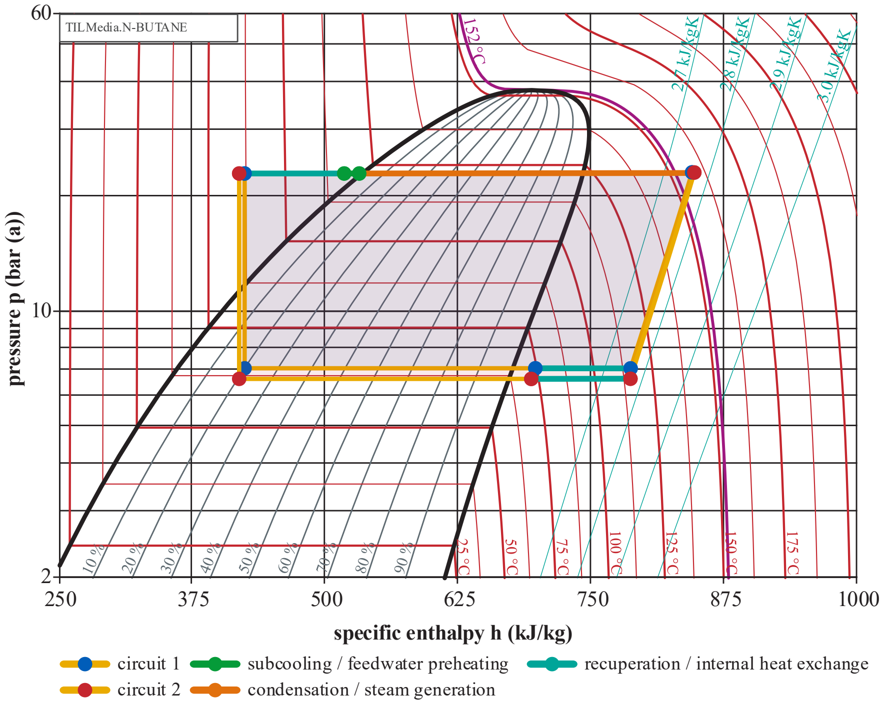

Figure 5. log(p)-h diagram for a steady state operating point of the test runs at SPH's testing facility, representing the design point of the steam generating heat pump unit

3.2. Operational results from the steam generating heat pump as part of the AHEAD system integrated in the Takeda site

Until mid of October 2025, the AHEAD system was in operation for 188.5 h, with the SPH heat pump having produced 121.9 t of saturated steam at 2 bar(a). In order to generate this amount of steam, the steam generating heat pump delivered 78.09 MWh of heat and consumed 19.66 MWh of electrical energy.

$$\text{SPF}= \frac{\int \dot{Q}_h \, dt}{\int P_{el} \, dt} = \frac{Q_h}{W_{el}} \tag{8}$$

A short-term seasonal performance factor (SPF) of 3.97 is calculated for the steam-generating heat pump according to Eq. 8. This short-term SPF summarizes all times, where the AHEAD system was active, and steam was produced. In the design simulations of the AHEAD system [17], an annual SPF for the steam generating heat pump of 3.3 for a saturated steam pressure of 2.3 bar(a) / 125°C and a SPF of 3.9 for a saturated steam pressure of 1.7 bar(a) / 115°C was calculated. Thus, operation slightly exceeds expectations from the design simulations.

The part load factor of the heat pump compressors ranged from 33.2% to 72.9% resulting in steam mass flow rates from 295 kg/h to 1317.1 kg/h with an electrical power demand between 54.1 kW and 195 kW. Steam pressures between 1.7 bar(a) and 2.8 bar(a) were reached, with the MVR system compressing it up to 11.3 bar(a) and 187°C. To achieve that, the MVR consumed 28.83 MWh of electrical energy. The electrical power demand ranged between 76.6 kW and 289.9 kW while operating at a rotational speed between 300 min^{-1} and 701 min^{-1}.

Within the operation time, 32 steady state operating points with at least 15 minutes duration were identified, applying the same restrictions to qualify as steady state operating point for the heat pump as for the test runs at SPH's testing facility as given in Table 1. Figure 6 shows the log(p)-h diagram for a typical steady state operating point lasting ca. 51 min, representing a part load factor of 63.6%. With the heat source inlet temperature being 70.0°C, the heat source outlet temperature being 64.4°C and the feedwater temperature being 96.3°C, a steam mass flow rate of 1039.6 kg/h at 2.0 bar(a) was reached. Thus, electric power consumption of the compressors was 167.7 kW resulting in a COP of 3.97 and a second law efficiency of 54.6%.

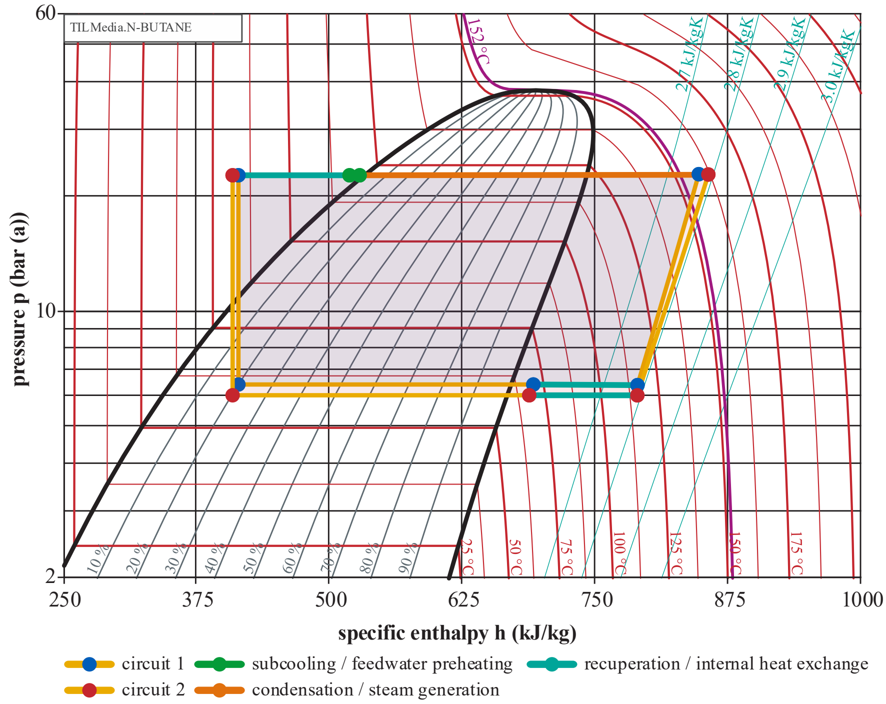

Figure 6. log(p)-h diagram for a steady state operating point of the steam generating heat pump, representing the typical operating state within the AHEAD system at the Takeda site

The log(p)-h diagram shows that the evaporation pressure of the evaporator 2 of the refrigeration circuit is lower than the one of evaporator 1. This pressure difference is due to the serial connection of the source side of evaporators, as shown in Figure 4, and amounts to 0.41±0.03 bar for all steady state operating points while operating at Takeda. Therefore, to reach the same condensation pressure, compressor 2 is operating at a higher pressure ratio, resulting in 3.3±1% more electrical power demand of compressor 2 than compressor 1.

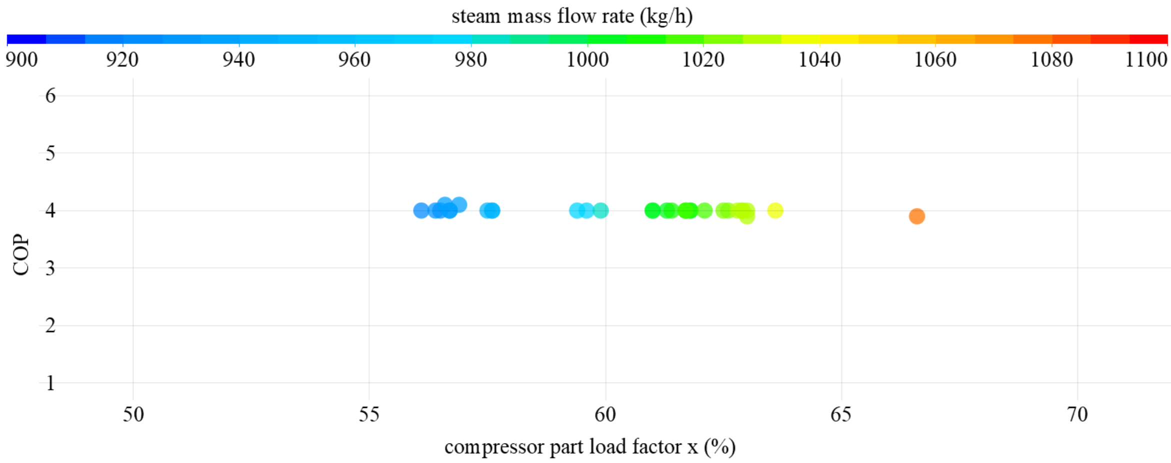

Figure 7. COP as a function of compressor part load factor with the steam mass flow rate represented in colour for steady state operating points at Takeda

Part load factors of the compressors for operation at the Takeda site are illustrated in Figure 7. They ranged from 56.1% to 66.6% resulting in steam mass flow rates from 923.3 kg/h to 1073.9 kg/h. As the source inlet temperature was kept constant at 70±0.1°C, the source outlet temperature at 64.7±0.3°C and the feedwater temperature at 96±0.4°C, a COP of 4.0±0.1 was reached resulting in second law efficiencies of 54.4±0.9%.

This indicates a constant efficiency of the piston compressors of the heat pump over varying part load for the studied range.

3.3. Overall results of the steam generating heat pump unit

Figure 8 shows the COP as a function of the temperature lift of the steady state operating points identified at SPH's testing facility and while operation at Takeda within the AHEAD system.

It visualizes the broad range of operation points that were tested at SPH (blue diamonds). The temperature lifts ranged from 40.0°C to 80.3°C, resulting in COP between 4.7 and 2.1. The heat source temperatures were between 49.9°C and 81.1°C and steam was produced with a minimum pressure of 1.59 bar(a) and a maximum pressure of 2.56 bar(a) at compressor part load factors ranging from 33.3% to 66.6%, resulting in steam mass flow rates between 258.6 kg/h and 941.8 kg/h while demanding 74 kW to 154.9 kW of electric power for the heat pump compressors.

The operation points at Takeda (orange dots) occur at the temperature lift of 52.7 – 54.3 K and achieve consistently a COP of ca. 4, resulting in a second law efficiency of around 54%. All steady state operating points including the test runs at SPH show a second law efficiency of 42.2% to 55.2% The second law efficiency of the trial runs at SPH amounts to 42.2 % for the highest temperature lift und 48.6% for the smallest lift. Operation points at SPH and Takeda with a temperature lift of ca. 53 K are in good agreement in terms of COP.

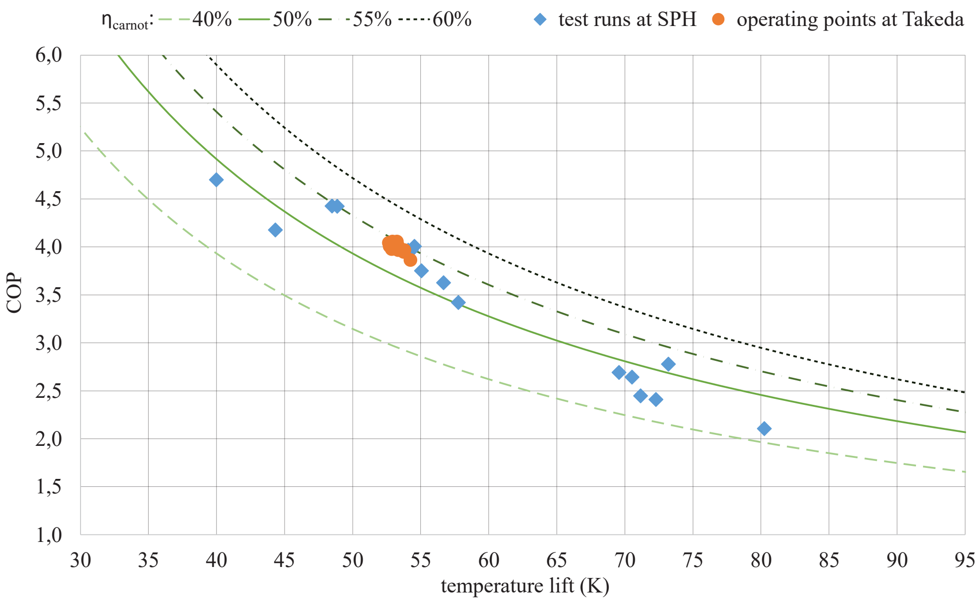

Figure 8. COP as a function of temperature lift for all steady state operating points of the two data sets, the lines represent second law efficiencies η_{Carnot} from 40% to 60% for a steam (heat sink) temperature of 120°C

4. Conclusions and outlook

The AHEAD system, an advanced heat pump system was successfully designed and implemented to provide steam at 11 bar(a) / 184°C at a pharmaceutical production site of Takeda in Vienna. It consists of a steam generating heat pump operated on n-butane by SPH and steam compressors. It is integrated at energy supply level and replaces fossil fuel boilers aiming for 1600 t/a of CO_2 savings annually. Two data sets were analysed: trial runs with the steam generating heat pump at the testing facility of SPH and the first weeks of operation of the AHEAD system at the Takeda site. The trial runs proved functionality of the heat pump and were also used to test conditions that cannot be created at Takeda to learn more about the behaviour of the heat pump. The trial runs covered temperature lifts from 40 to 80 K resulting in COP in the range of 4.7 to 2.1 with a maximum steam pressure of 2.53 bar(a). Until mid of October 2025, the AHEAD system was in operation for 188.5 hours, with the SPH heat pump having produced 121.9 tons of saturated steam at 2 bar(a) with a short-term SPF of 3.97, which slightly exceeds expectations from design simulations. The second data set from operation of Takeda showed an average COP of 4 for a temperature lift of ca. 53 K for the steam generating heat pump. The second law efficiency amounts to 54%. The AHEAD system was fully operational, the MVR was also running and yielded 11 bar(a) and 184°C.

The AHEAD system will be scientifically monitored and further optimized for at least 4000 h allowing for more detailed analysis of the operation. The aim of optimization is to maximize steam output while minimizing energy requirements.

Acknowledgements

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