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Conceptual design and integration of a steam-generating unit into a high-temperature heat pump

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Abstract

Process heat accounts for a major share of total industrial energy demand. Various industrial sectors require temperatures between 100 °C and 200 °C, using steam as the main energy carrier. This demand is primarily met by fossil-fueled boilers, making it a key target for decarbonization. Recent research has focused on steam-generating heat pumps (SGHPs) as a promising alternative for supplying industrial steam by utilizing low-temperature waste heat. This study presents the conceptual design and integration of a steam generating unit into an existing 35 kW_{th} high-temperature heat pump (HTHP) test rig. Various options for steam generation using HTHPs were considered in a first step, distinguishing between direct steam generation at the heat pump condenser and indirect steam generation using a flash tank. Due to its higher efficiency, compactness and lower investment costs, the expansion of the existing HTHP is based on direct steam generation using a plate-and-shell heat exchanger (PSHE). The study further describes the integration concept and the most important design parameters for the PSHE. Future work will include the mechanical commissioning and experimental characterization of the steam generation process, followed by the development of detailed simulation models for system upscaling and techno-economic analysis. The presented concept provides a practical approach for adapting existing HTHPs for steam supply and thus contributes to the wider implementation of SGHPs in industrial processes.

Keywords: High temperature heat pump; steam generation; industrial process heat, system integration

1. Introduction

The industrial sector accounts for 29 % of Germany's total final energy consumption [1]. Around two-thirds of this industrial energy demand can be attributed to the supply of process heat. In 2023, process heat accounted for around 470 TWh, corresponding to approximately 21 % of Germany's total final energy demand [2]. The majority of this process heat is still provided by fossil fuels, with renewable energies accounting for just 6 % in 2020 [3]. Consequently, the decarbonization of industrial heat supply represents one of the key challenges in achieving national and international climate targets. To decarbonize the industrial sector technologically and economically viable alternatives are required. In this context, direct electrification of process heat supply using high-temperature heat pumps (HTHPs) is a promising solution. HTHPs can efficiently utilize low-temperature waste heat as a heat source and upgrade it to the required temperature. Particularly the temperature range of 100 °C – 200 °C would be suitable for HTHP integration. There is a high demand for process heat in this range, especially in the paper and food industries [4]. However, most of this heat is required in the form of steam for processes such as drying, evaporation, pasteurization and sterilization, which makes the integration of HTHPs more challenging.

In recent years, significant progress has been made in the research and development of HTHPs for heat supply above 100 °C [5] and a current focus is on so called steam-generating heat pumps (SGHP). Klute et al. [6] provide a comprehensive overview of the current state of SGHPs. They present existing SGHPs and identify

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key barriers to their industrial implementation. The authors analyzed over 40 SGHP designs and classified them into five fundamental concepts, distinguishing between steam generation directly at the heat pump condenser and indirect steam generation via flash evaporation into a flash tank. D'Alessandro et al. [7] further developed the work of Klute et al. by focusing on optimization strategies and the selection of refrigerants for different SGHP concepts. Cycle design optimizations using internal heat exchangers (IHX) and refrigerant injection, as well as two-stage and cascade systems, to increase efficiency and expand the possible temperature range for industrial steam generation are investigated.

Numerous theoretical studies on SGHPs are already available and experimental research has intensified during the last years. However, detailed descriptions of modifying existing HTHP systems for steam generation are rarely published. Many studies focus on either new HTHP setups or integration of commercially available SGHPs at industrial sites. Practical case studies of modifications and necessary peripheral adaptations of existing HTHPs are rarely reported. Therefore, this study focusses on the adaptation of an existing HTHP for direct steam generation, using a plate-and-shell heat exchanger (PSHE) as heat pump condenser. It gives an overview of the two relevant options for steam generation and describes the existing HTHP test rig as well as the planned modification for steam generation. Challenges and limitations regarding the application range of the existing HTHP are outlined.

2. Steam generation concepts using HTHPs

Several technical concepts have already been proposed for generating steam using HTHPs. As the existing HTHP considered in this study is based on a closed-loop vapor compression cycle, the following analysis focuses on modification options applicable to this configuration. Essentially, there are two main approaches to steam generation, direct steam generation at the heat pump condenser, and indirect steam generation by flash evaporation in a separate vessel, with the HTHP continuing to supply pressurized hot water. Both concepts are described in the following section, highlighting their thermodynamic characteristics, advantages and technical challenges, as well as examples of their implementation found in the literature.

2.1. Direct steam generation

Generating the steam directly on the heat sink side of the heat pump condenser is the most effective way to produce steam and as stated by Klute et al. [6] also the most common type of SGHPs. The design of the condenser can vary, depending on the application. Examples include brazed plate heat exchangers (BPHE), shell and tube heat exchangers (STHE), and PSHE. Some applications also use additional steam separators to avoid water droplets and obtain a certain steam quality. The steam temperatures are limited by the maximum possible condensation temperatures of the refrigerant. To achieve higher steam pressures and temperatures, recompression of the vapor, either mechanically or thermally, is possible. In the following a comprehensive overview of some experimental studies is given.

Uhlmann et al. [8] investigated a 70 kW butane heat pump with a BPHE as a condenser for direct steam generation at 1.4 bar(a). A second BPHE enables the steam to be superheated stably. The system includes an additional steam separator and the option for mechanical vapor recompression (MVR) using a turbo compressor, thus enabling flexible operation for different process steam requirements. Hu et al. [9] presented experimental investigations of direct steam generation using a cascaded high-temperature air heat pump that produces saturated steam with a STHE at temperatures of up to 125 °C. A vapor-liquid separator downstream of the condenser ensures dry steam at the outlet. Benkert et al. [10] recently published a study in which a HTHP from Johnson Controls, also using butane as the refrigerant, with a maximum thermal capacity of 125 kW is investigated. The HTHP can be operated in three different modes, providing pressurized hot water, wet steam, and dry steam at temperatures of up to 120 °C. The steam is generated directly at the heat pump condenser, which is designed as a PSHE.

In addition to the laboratory systems listed above, SGHPs are increasingly being tested in industrial applications. Wemmers et al. [11] demonstrated the integration of a 160 kW butane (R600) heat pump into a paper mill. Using a waste heat source of 60 °C, the SGHP produces saturated steam at the heat pump condenser at pressures of up to 3.4 bar(a). As part of the Push2Heat project, a cascaded SGHP from SPH Sustainable Process Heat GmbH is being used to generate saturated steam at 2 bar(a) using a PSHE in a paper mill [12]. At the same paper mill, a single-stage SGHP from Heaten is being tested for generating saturated steam at 2 bar(a), with recompression to 10 bar (180 °C) using a turbo compressor from DLR [13]. Within the SPIRIT Heat project, Mayekawa is testing a cascaded SGHP for saturated steam generation at 4 bar(a) for prawn processing in Norway [14].

2.2. Indirect steam generation

For indirect steam generation a closed-loop heat pump is used as the bottom cycle to supply pressurized hot water to a top cycle, where either an evaporator or flash tank is used to generate the steam. Using an evaporator to generate steam requires a closed-top circuit in which pressurized hot water circulates. In contrast, the flash tank option requires an open circuit. The pressurized hot water is expanded via a throttle valve into the flash tank, where it partially evaporates into saturated steam. The saturated, non-evaporated liquid is then mixed with make-up water, compensating for the removed steam mass flow rate, and fed back into the heat pump condenser. The saturated steam temperature is limited by the maximum supply temperature of the heat pump and is slightly lower due to the expansion process. Subsequent recompression of the steam can also be carried out here to achieve higher temperature and pressure levels.

Kang et al. [15] investigated a HTHP system with an IHX and the refrigerant R245fa. Using a flash tank, this system generates saturated steam in the range of 115 °C to 120 °C. Similarly, Lee et al. [16] developed and implemented an HTHP with a heating capacity of 350 kW for the use in a waste scrubbing process in a chemical plant. This system also generates saturated steam in the range of 110 °C - 120 °C via flash evaporation. Waste heat of 50 °C - 70 °C was used as the heat source. Andersen et al. [17] tested the SGH165 [18] heat pump, which is a commercially available product from KOBELCO designed for industrial steam supply up to 175 °C. The system uses a flash tank to produce saturated steam at approximately 110 °C. The steam is then compressed in a separate steam compressor to reach temperatures of up to 175 °C.

A comparative analysis of the two approaches for steam generation was conducted by Liu et al. [19]. The study investigated a direct steam generating heat pump (DSHP) and a flash steam generating heat pump (FSHP) using R1233zd(E). The results showed that both configurations were technically feasible, offering different advantages depending on the system boundary conditions. Under comparable operating conditions, the FSHP achieved higher steam production, while the DSHP had a higher coefficient of performance *(COP)* due to lower condensation pressures and correspondingly reduced compressor work. Combining direct steam generation at the heat pump condenser with mechanical vapor recompression (MVR) generally enables the highest overall *COP*s.

3. Experimental setup

The HTHP under consideration has a maximum thermal output of 35 kW and was first introduced by Jeßberger et al. in 2022 [20]. Within several studies Jeßberger et al. conducted a detailed investigation of the part-load behavior of the HTHP and its corresponding optimization in relation to heat supply in the form of pressurized hot water [21–23]. To provide a comprehensive overview the HTHP concept is reiterated briefly using the flowchart shown in Figure 1.

The single-stage vapor compression HTHP consists of the refrigerant circuit (illustrated in black) and two secondary water circuits that function as heat source (illustrated in dark blue) and heat sink (illustrated in red). As working fluid, the non-flammable hydrochlorofluoroolefine (HCFO) R1233zd(E) with a low global warming potential (GWP) of 1 CO_2e and an ozone depletion potential (ODP) of 0.00034 [24] is used, enabling a safe operation.

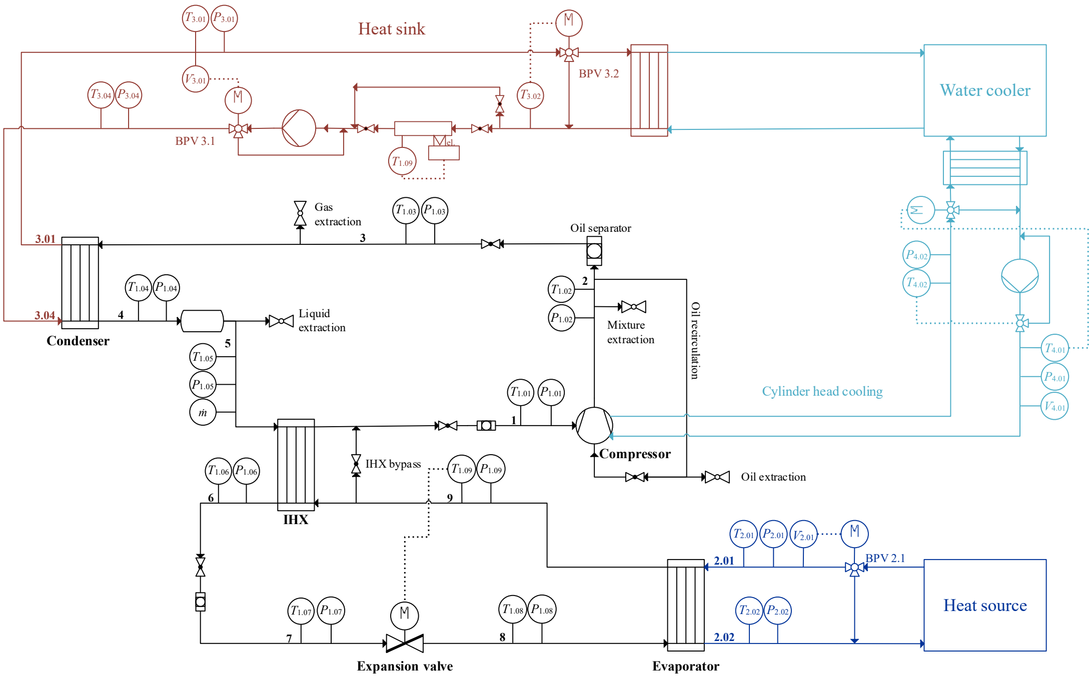

Figure 1: Schematic of the existing laboratory HTHP based on [22]

After compression (state 2), the refrigerant is at a higher pressure and temperature. It then passes through an oil separator to remove entrained oil droplets and ensure optimum heat transfer in the condenser (state 3). The refrigerant is slightly subcooled at the outlet of the condenser (state 4) and then flows through the IHX as described above. After passing through the IHX, the working fluid undergoes isenthalpic expansion in the expansion valve (state 7), before entering the evaporator (state 8). The expansion valve is controlled to maintain a defined superheat at the evaporator outlet (state 9). All heat exchangers are designed as plate heat exchangers in counterflow configuration. To record the thermodynamic state at each point of the cycle, pressure and temperature sensors from OMEGA Engineering GmbH are installed upstream and downstream of every component. In addition, a Coriolis flow meter is placed in the liquid line downstream of the refrigerant receiver (state 5). Two further special features of the HTHP are the sampling points for liquid, gaseous, and oil-refrigerant mixtures, as well as the cylinder head cooling (illustrated in light blue). The latter can be used for waste heat recovery and to reduce the discharge temperature, as discussed in more detail in [23].

The heat source circuit is equipped with an electric heater from HB-Therm AG, which allows a flexible adjustment of the heat source inlet temperature $T_{2.01}$. The volumetric flow rate through the evaporator is controlled by a three-way valve to achieve the desired return temperature $T_{2.02}$. The heat sink circuit is also a closed water circuit that is connected to the house cooling network via a plate heat exchanger. This circuit is driven by a frequency-controlled circulation pump from Grundfos GmbH. A three-way valve located downstream of the pump regulates the flow rate through the HTHP condenser, thereby controlling the heat sink outlet temperature $T_{3.01}$. After leaving the heat pump condenser, the hot water passes through the plate heat exchanger, transferring heat to the cooling network and cooling down accordingly. The three-way valve enables the return temperature to the heat pump condenser to be adjusted as required.

The original design of the heat pump corresponds to a heat source inlet temperature of 60 °C and a heat sink outlet temperature of 105 °C [20]. However, in previous studies the operating range was extended beyond this design point to investigate off-design and part-load behavior. Jeßberger et al. [22] demonstrated heat sink outlet temperatures of up to 140 °C using the previously described HTHP test rig. For the experimental investigations, a defined base scenario was selected with a heat source temperature of 60 °C and a heat sink outlet temperature of 120 °C [22]. Under these conditions, a *COP* of up to 2.75 was achieved at the design compressor speed of 1517 rpm (50 Hz). Further optimization of the suction gas superheat and internal heat exchanger bypass settings resulted in *COP* improvements of up to 12.7 %. Additionally, the results demonstrated a strong dependency of the *COP* on part-load operation, with efficiency gains achieved at reduced compressor speeds [22]. To date, all experimental work on the existing HTHP has been limited to pressurized hot water supply. The system modifications and extensions required to enable further investigations into steam generation are presented in the following chapter.

4. Steam generation unit

Based on the literature review presented in Chapter 2 and the comparative assessment of both steam generation concepts, direct steam generation was selected for integration into the existing HTHP. The selection was made after evaluating thermodynamic performance, integration aspects, and investment cost. Despite the simpler integration of a flash-tank system, the direct steam generation concept, using a PSHE, was ultimately chosen for this work mainly due to its higher efficiency and compactness. The following section therefore discusses the design of the PSHE and its integration into the HTHP test rig described above.

4.1. Design of the plate-and- shell heat exchanger

To realize this approach, the PSHE was designed together with the manufacturer Vahterus OY. As shown in Figure 2 the PSHE is configured so that the plate pack has a significantly smaller diameter than the shell and is positioned eccentrically below the centerline of the shell. The plate pack is fully submerged in water, while the upper part of the shell functions as vapor space. This design enables phase separation and ensures that only saturated steam can exit at the top of the PSHE.

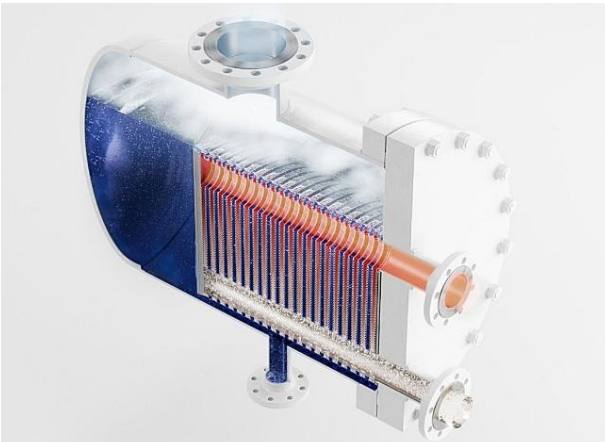

Figure 2: Layout of the Vahterus PSHE for steam generation [25]

The relevant design boundary conditions were defined based on previous measurement series by Jeßberger et al. [22]. With the existing HTHP, a maximum condensation pressure of around 18 bar(a) can be achieved, corresponding to a maximum condensation temperature of approximately 127 °C. This upper limit significantly affects the achievable heat sink temperatures, particularly for saturated steam generation. Figure 3 illustrates the correlation between the condensation temperature of the refrigerant and the achievable heat sink temperature, comparing pressurized hot water supply with saturated steam generation. The figure shows the temperature profiles of a heat pump condenser in counterflow operation supplying pressurized hot water (left) and saturated steam (right) to the heat sink at the same supply temperature. The black lines represent the refrigerant temperature, while the red lines indicate the temperature profile of the heat sink. The minimum temperature difference is highlighted as the pinch point (ΔT_{PP}).

In the case of pressurized hot water supply (Figure 3, left) two-phase heat transfer only occurs on the refrigerant side whereas heat is transferred sensibly on the heat sink side. The continuous temperature increase of the water along the heat exchanger leads to a locally occurring pinch point towards the hot side of the condenser and the outlet temperature on the heat sink side exceeds the refrigerant condensation temperature.

In contrast to pressurized hot water supply, steam generation is characterized by two-phase heat transfer on both sides (Figure 3, right). The heat sink temperature profile remains constant throughout the evaporation process due to the latent heat transfer. As a temperature crossover in the heat exchanger is not possible, the maximum achievable condensation temperature of the refrigerant therefore limits the maximum saturated steam temperature. In the presented case, the maximum achievable steam temperature is therefore limited to approximately 120 °C, considering a sufficient pinch point. Thus, saturated steam generation requires higher refrigerant condensation temperatures than pressurized hot water supply for the same heat sink outlet temperatures.

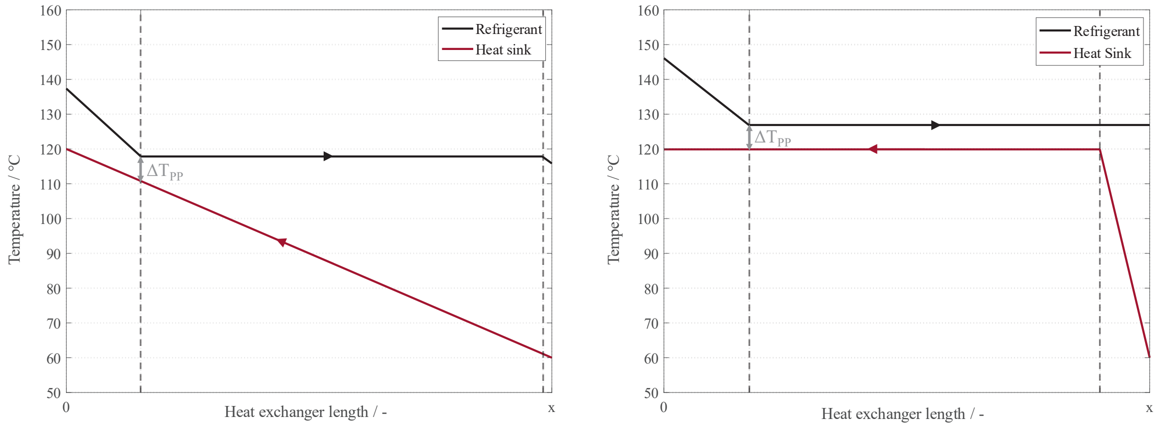

Figure 3. Temperature profile of a condenser for pressurized hot water supply (left) and steam supply (right)

The PSHE was designed accordingly for a maximum saturated steam temperature of 120 °C and will be characterized for the different operating points listed in Table 1.

Table 1. Operating points for steam generation

	Shell side (cold): water					Plate side (hot): R1233zd(E)	
Operating points	Outlet temperature	Pressure	Inlet temperature	Thermal capacity	Steam mass flow rate	Condensation pressure	Condensation temperature
1	105 °C	1.20 bar(a)	60 °C	25.5 kW	36.00 kg/h	14.4 bar	115.48 °C
2	110 °C	1.43 bar(a)	60 °C	24.2 kW	35.64 kg/h	15.5 bar	119.19 °C
3	115 °C	1.70 bar(a)	60 °C	22.7 kW	33.50 kg/h	16.9 bar	124.00 °C
4	120 °C	1.98 bar(a)	60 °C	19.9 kW	29.16 kg/h	18.2 bar	127.50 °C

The inlet water temperature to the PSHE is set to 60 °C, and the thermal capacities ($\dot{Q}_{\mathrm{th}}$) correspond to those of the pressurized hot water generation at the respective refrigerant condensation pressures. The expected steam mass flow rates ($\dot{m}_{\mathrm{steam}}$) for each operating point can then be determined from the enthalpy difference between the heat sink inlet ($h_{\mathrm{sink,in}}$) and outlet ($h_{\mathrm{sink,out}}$) as follows:

$$\dot{m}_{steam} = \frac{\dot{Q}_{th}}{\left(h_{sink,out} - h_{sink,in}\right)}. \tag{1}$$

4.2. Conceptual design and system integration

In addition to steam generation, the possibility of supplying pressurized hot water should also be maintained. Therefore, a second heat sink circuit is planned for integrating the PSHE into the existing HTHP, as shown in Figure 4 (illustrated in green). The setup and operation of the steam circuit is described below based on the flowchart.

The PSHE is integrated into the refrigerant circuit via a bypass valve located upstream of the current heat pump condenser. This enables flexible switching between pressurized hot water and steam supply. In steam generation mode, the refrigerant flows through the plate pack of the PSHE, where it condenses. The incoming water on the secondary shell side subsequently evaporates and exits as saturated steam at the top of the shell. A control valve at the steam outlet of the PSHE regulates the required evaporation pressure of the water in the PSHE. The steam then flows through a plate heat exchanger, which is connected to the house cooling network, where it condenses. A three-way valve regulates the volumetric flow rate of the cooling water through the steam condenser, thereby controlling the corresponding condensation pressure. The condensed steam is further subcooled in a second plate heat exchanger, also coupled with the house cooling network. Similar to the existing heat sink water circuit described above (see chapter 3), the return temperature $T_{5.04}$ is set via a three-way valve that regulates the flow of condensate through the plate heat exchanger. To compensate for control related fluctuations and prevent the pump from entrapped air, the subcooled condensate is fed into an electrically heated buffer tank. The water in this tank is maintained at the required return temperature to the condenser. A frequency-controlled pump keeps the water level in the PSHE constant by supplying a condensate mass flow rate that corresponds to the amount of steam exiting the PSHE.

To characterize the thermodynamic state at each point, pressure and temperature sensors are installed before and after each component in this cycle. In the liquid phase, a Coriolis flow meter is used to determine the steam mass flow rate.

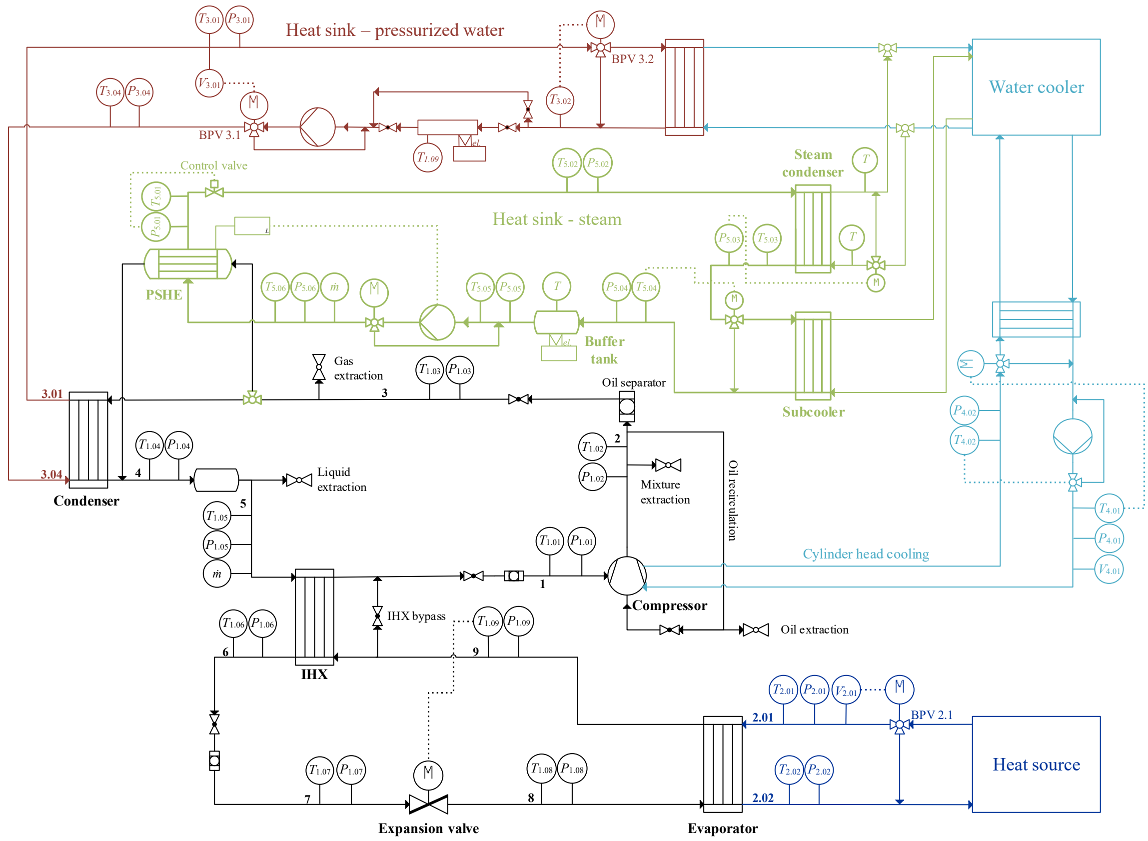

Figure 4: Planned integration of the PSHE into the existing HTHP

5. Summary and Outlook

This work presented the conceptual design and integration of a steam-generating unit using a PSHE into an existing HTHP test rig. The objective was to extend the system's capability from pressurized hot water supply towards direct steam generation up to 120 °C. The two relevant solutions for steam generation using HTHPs were considered, and the method of direct steam generation using PSHE was selected as the most feasible option. The integration concept was developed, key design parameters were defined, and the modifications required for the test facility were outlined. Special attention was given to the challenges associated with the higher condensation temperatures required for steam generation.

The next steps will involve the final mechanical integration and commissioning of the modified system. Subsequent experimental investigations will focus on characterizing the steam generation process, determining achievable operating ranges, and evaluating system performance under varying load conditions. Based on the measured data, detailed simulation models will be developed to enable techno-economic analyses of heat pump-based steam supply and upscaling of the system. The presented concept thus provides the foundation for future research on the practical realization and optimization of SGHP systems, contributing to the decarbonization of processes such as drying, evaporating, pasteurization and sterilization within several industries.

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