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Industrial high temperature heat pump for steam and hot water production

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Abstract

In industrial processes, heat is often required in the form of saturated steam. Due to their thermodynamic process, compression heat pumps are ideal for converting waste heat back into high quality saturated steam. The advantage over steam compressors is the ability to perform the phase change efficiently. An industrial high temperature heat pump capable of generating saturated steam up to approx. 6 bar absolute (approx. 160°C) or hot water at approx. 165°C is presented in this paper. For this purpose, a self-developed high-performance piston compressor is used, which was specially designed for high temperature applications with HFO refrigerants, such as R1336mzz-Z or R1233zd.The article presents two industrial applications in which large amounts of CO_2 are saved or avoided by using innovative high temperature heat pumps. One is 2 bar absolute steam production from cooling water heat of combined heat and power systems, used in the gelatine production. The other is the production of 130°C hot water for a drying process in the recycling industry. The paper shows that steam production in the industry with high temperature heat pumps is possible.

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Keywords: high temperature heat pump, steam, HFO, R1233zd;

1. Introduction

Global warming, climate change and the dependence on fossil fuels are defining challenges in the coming years and decades. In order to achieve the goals set by the EU for 2030 [1], a variety of measures are necessary. In addition to the expansion of renewable energies, it is essential to increase energy efficiency and thus reduce primary energy consumption.

About 21% of the total CO_2 emissions in Europe are due to industry [2]. Today, process heat in the range above 100°C is mainly generated with the help of fossil fuels, such as natural gas or fuel oil. A large part of the process heat in the range up to 200°C is used in the form of saturated steam. Saturated steam has the advantage of a large energy content when using the phase change and at the same time low transport costs from the point of generation to the consumer.

In recent years, the use of heat pumps as an alternative to fossil fuel heat generators has become increasingly popular for heating residential buildings. Here, mainly electrically driven compression heat pumps are used, which use environmental heat (outside air, geothermal heat) as a heat source to generate the required useful heat. When used with renewable electricity, quasi CO_2-free heat generation is thus possible.

This article shows the possibility of providing process steam or hot water from unused industrial waste heat with the help of compression heat pumps. The ThermBooster system can generate temperatures up to 165°C, or saturated steam pressures up to 6 bar absolute. The system is based on a piston compressor specially developed for use in industrial high temperature heat pumps. HFOs such as R1233zd are used as refrigerants.

Two industrial applications are shown. On shows the use of the system to produce 2 bar absolute saturated steam for use in the gelatine production. The other shows an innovative heat concept in the production of an innovative thermoplastic compound material, where the high temperature heat pump delivers 130°C hot water for a drying process.

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2. ThermBooster pilot system and process

2.1. Compressor

The core of the high temperature heat pump is a specially developed 4-cylinder piston compressor with a displacement of approx. 540 m³/h at 1500 RPM. The compressor is designed for up to 35 bar on the high-pressure side and 18 bar on the low-pressure side. Hot gas temperatures of 250°C and suction gas temperatures of 200°C are possible without any problems. The compressor is optimized by a patented valve system for HFO refrigerants of the latest generation (e.g. R1233zd, R1336mzz-Z) and achieves high isentropic and volumetric efficiencies. The valve system is characterized by an optimized arrangement and the use of the available area, thus reducing the pressure drop in the valve system to a minimum while maintaining a low clearance volume. First measurements on the testbed have shown isentropic efficiencies η_{is}, with R1233zd(E) as working fluid, in the range of 85%-95% for pressure ratios between 2,5 and 3,5. These values are calculated by measuring the pressure and temperature at compressor inlet and outlet and comparing the enthalpy difference according to formular 1. The volumetric efficiencies showed to be between 92% and 95%.

$$\eta_{is} = \frac{h_{Out,ideal} - h_{in}}{h_{Out,measured} - h_{in}} \tag{1}$$

To achieve long lifetimes and service intervals with these high temperatures, the heat pump is equipped with an oil conditioning system which always keeps the oil in a temperature range which is as low as possible, but still high enough to prevent too much refrigerant solving into the oil. The cylinder surface of the compressor together with its piston and piston rings is optimized for very low oil transport into the refrigerant circuit. It is also equipped with an oil separator in the crankcase ventilation system to reduce oil transport into the refrigeration circuit to nearly zero. Up to now, no detailed measurement was done but currently no oil transport could be observed. Depending on the refrigerant used, different type of oils will be used. For R1233zd(E) POE (Polyolester) or CE (Complexester) oils are used.

2.2. System layout

The system is designed as a compression heat pump with internal heat exchanger. Figure 1 shows the schematic structure of the system while Figure 2 shows the realised design as a CAD model.

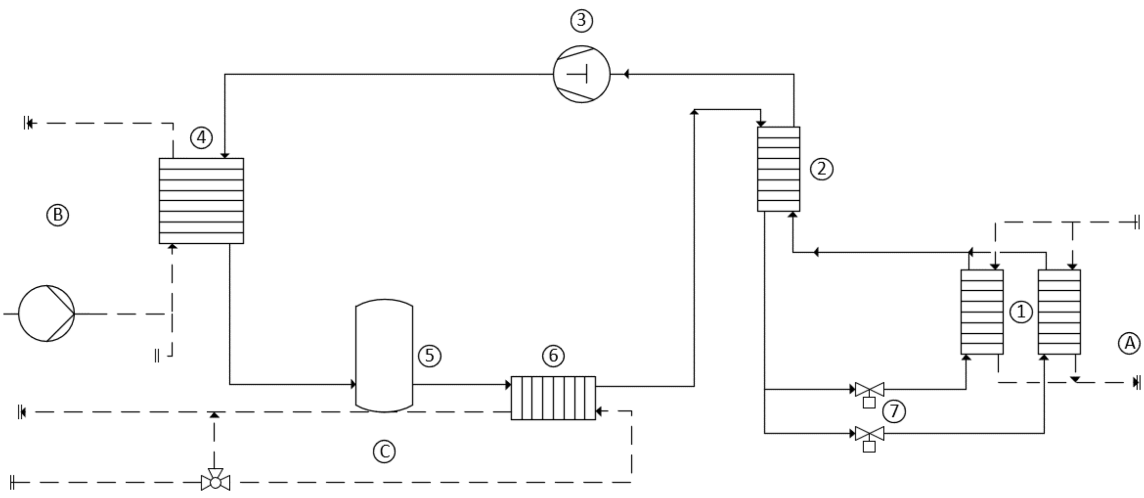

Fig. 1: principle P&ID of the heat pump

Table 1: legend for figure 1-3

Part	Description
1	Evaporator
2	Internal Heat Exchanger
3	Piston Compressor
4	Condenser / Steam Boiler
5	Receiver
6	Subcooler
7	Expansion Valve
A	Heat Source Circuit
B	Heat Sink Circuit for steam production including feed water pump
C	Subcooler Circuit for hot water

Highly efficient plate heat exchangers are used as evaporators and as internal heat exchangers. The condenser in the refrigeration circuit, which is also the steam generator in the heat sink circuit, is implemented as a Plate & Shell heat exchanger.

Plate & Shell heat exchangers offer for this application a good combination of efficiency of heat transfer from refrigerant to water and the required robustness for use in industrial steam systems. Evaporation is controlled by electronic expansion valves. To further increase efficiency, an additional subcooler has been integrated. With this subcooler, thermal energy as hot water can be extracted in parallel to the steam generation by subcooling the working fluid to lower temperatures to use it, for example, for feed water preheating or to feed it into another heating circuit.

For optimal oil conditioning, the oil sump of the compressor is equipped with a water jacket, which serves to preheat the oil and expel the dissolved refrigerant from the oil, as well as for oil cooling in high temperature operation. The required water is heated or cooled to the required temperatures by a conditioning unit integrated on the frame of the heat pump.

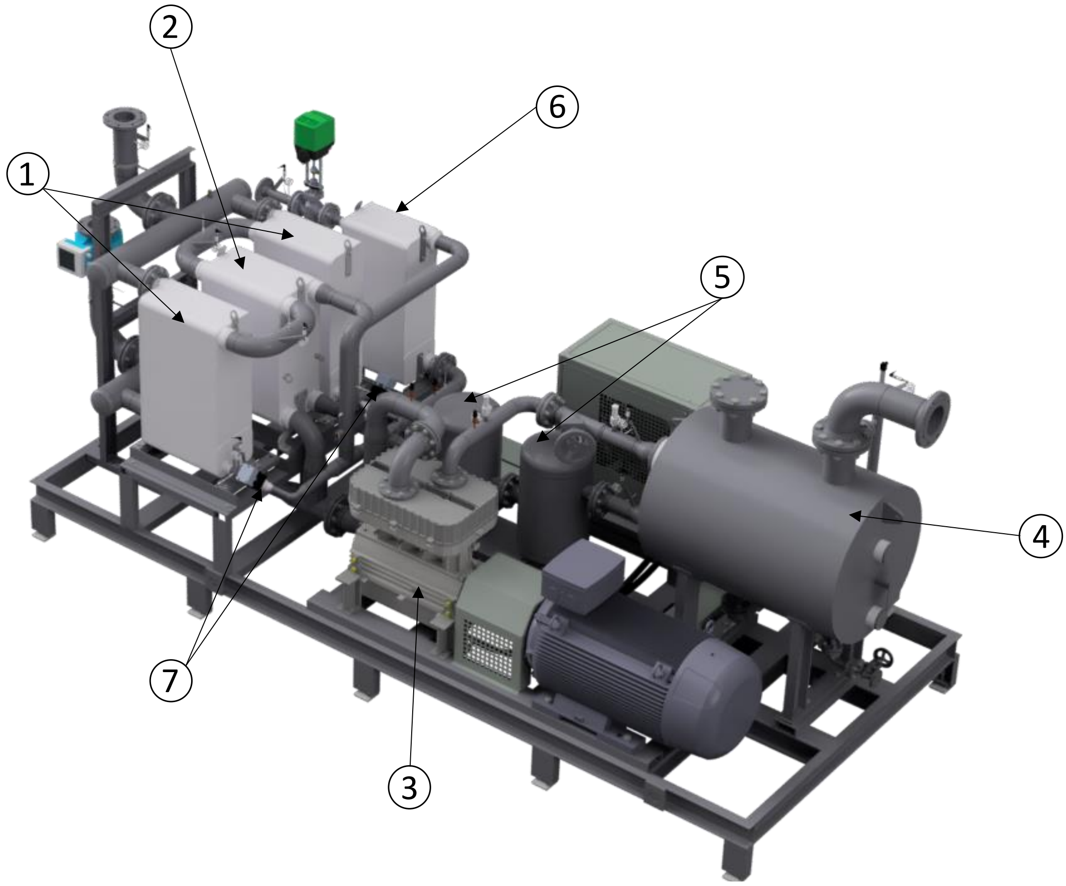

Fig. 2: CAD model of the ThermBooster

2.3. Thermodynamical cycle

The system operates as a compression heat pump with internal heat exchanger. Figure 3 shows the cycle in the log pH diagram for R1233zd(E).

Here, the process is as follows:
1) Evaporation with low superheat.
2) Superheating in the internal heat exchanger
3) Compression in piston compressor
4) Desuperheating and condensation
6) Subcooling in water-cooled subcooler
2) Subcooling in internal heat exchanger
7) Expansion in expansion valve and evaporator

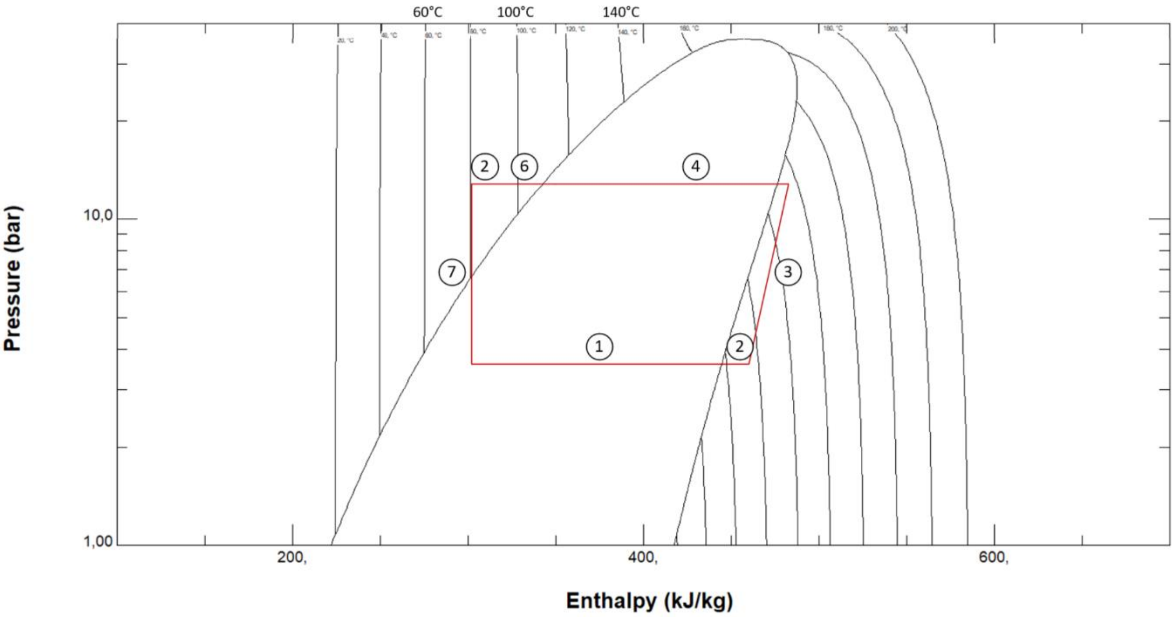

Fig. 3: log PH diagram of the thermodynamical cycle

3. Applications in industry

In the following, several project examples in industry are presented. The examples come from the food and recycling sector and show the wide range of possible applications of such systems for the generation of process heat with heat pumps. In addition to the integration, the effects on CO2 emissions are shown with the help of model calculations.

3.1. Gelatine production

Gelatine is mainly obtained from animal components, such as hides and bones of cattle and pigs. For this purpose, after thorough cleaning, the animal products must be pre-treated with the aid of acids so that the gelatine can then be extracted. The extraction is then carried out in several stages using hot water, with the water temperature being increased at each stage. The gelatine solution obtained, which now contains 2-5% gelatine, is then purified of solids before being concentrated to about 20-40%. This is usually done by vacuum evaporator. After leaving the concentration, the gelatine is thermally sterilized. Depending on the desired product (powder or sheet gelatine), various thermal drying processes are now used.

It can be clearly seen that thermal energy is required for most of the different process steps. Most of the thermal energy is required for the drying processes, where also the highest temperatures are needed.

3.1.1. Boundaries/ pre installation status

Currently, heat is generated by a gas-fired steam generator and several cogeneration units, which are used to supply electricity to the plant. There are two heat rails at the plant. A hot water rail at about 85°C and a steam rail at 2 bar absolute, corresponding to 120°C. The hot water rail is mainly fed by the cooling water heat from the CHP units and is used to provide process heat and heat for heating the buildings. The steam line is used exclusively to provide process heat. Since the demand for floor heating varies greatly from season to season and the demand for hot water is also relatively low, there is unused heat at this temperature level, most of which is now discharged to the environment via dry coolers. Figure 4 schematically shows the current situation in heat generation.

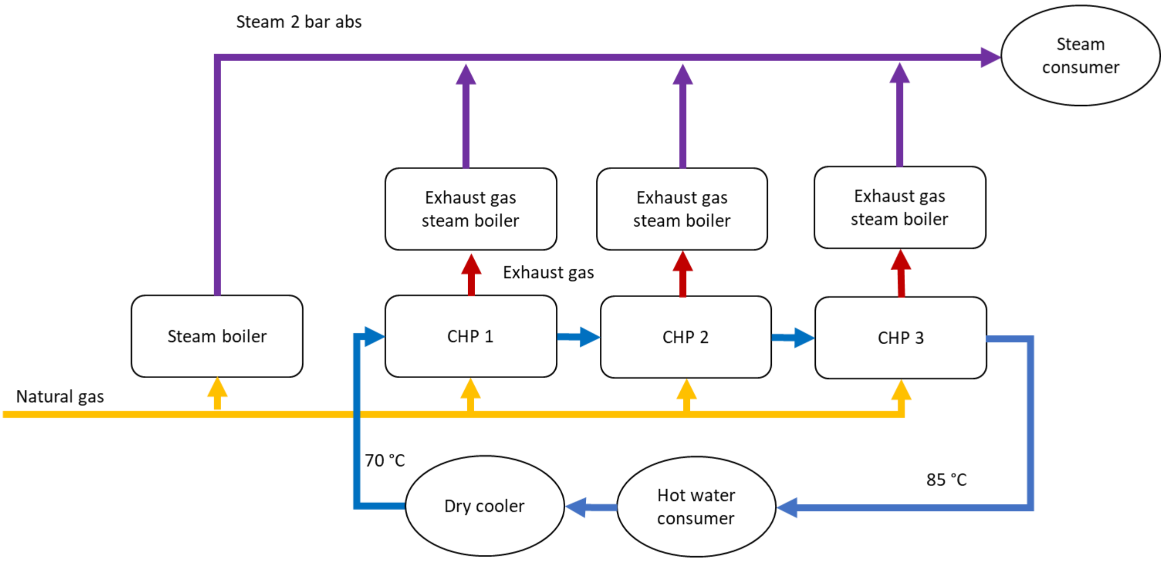

Fig. 4: current heat generation concept

3.1.2. Integration

In the future, the heat pump will replace the dry coolers and ensure that 100% of the heat generated is used on the 80°C hot water rail for production and space heating and not-longer wasted into the environment. For this purpose, the heat pump is integrated into the circuit parallel to the existing consumers and thus uses the 80°C heat rail as a heat source.

The heat pump used corresponds to the system presented in chapter 2, only without using the subcooler. Figure 5 shows the planned integration. The heat pump has to cool down the heat source to 70°C in order to use all available energy of the cooling water, because this 70°C is needed to be able to cool the CHP units.

Table 2 shows the integration conditions and the resulting performance data of the heat pump. All results are currently mostly based on simulations in combination with first results from the testbed. The heat pump will be installed beginning of 2023. The heat pump evaporates at about 67°C and condenses at about 125°C, giving an internal temperature lift of 58K. The theoretical Carnot efficiency related to evaporation and condensation temperature results from formula 2 to 6.9, this means that we reach here with the achieved COP of 4,4 a Carnot quality of 64% related to evaporation and condensation temperature. This is one used definition of the Carnot quality, another possibility is to calculate it related to the hottest and coldest process temperatures which are here the steam temperature of 120,2 °C and the heat source outlet temperature of 70°C. Using these temperatures, the Carnot quality reduces to 56%.

$$COP_{Carnot} = \frac{T_{Cond}}{T_{Cond} - T_{Evap}} \tag{2}$$

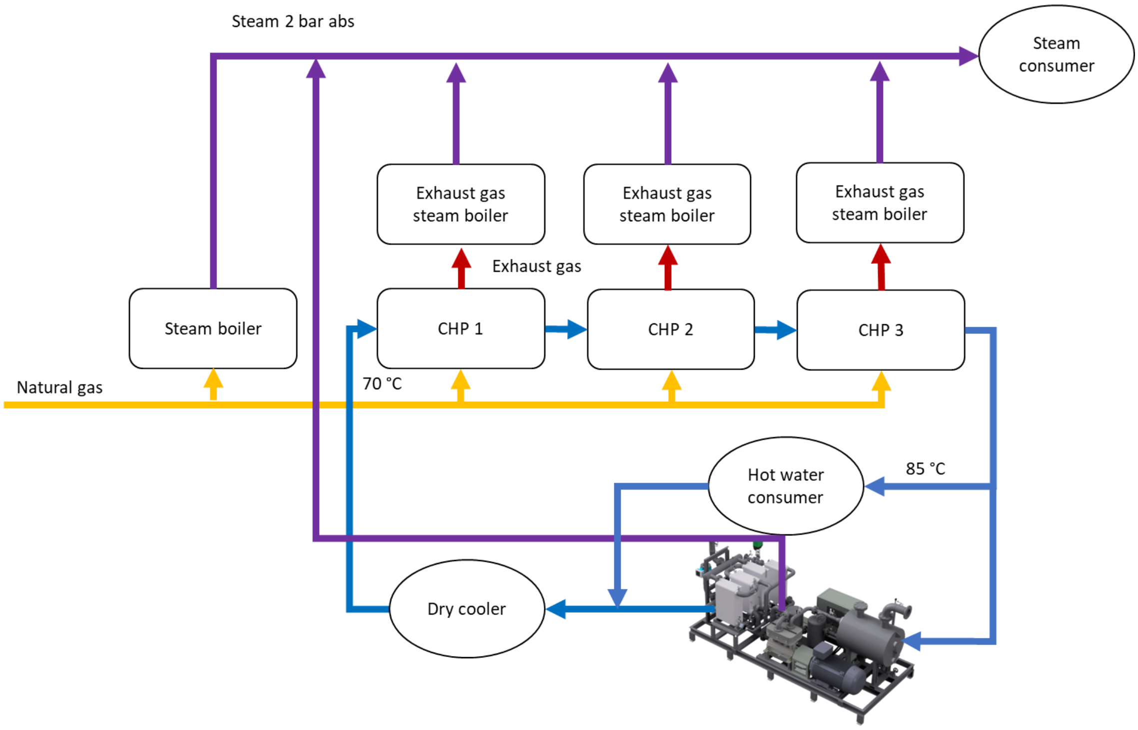

Fig. 5: planned integration of the heat pump

Table 2: boundary conditions and simulated performance data for heat pump integration

Parameter	**Value**
Heat Source Inlet	85°C
Heat Source Outlet	70°C
Feedwater In	85°C
Saturated Steam Pressure	2 bar absolute
Thermal Output	514 kW (812 kg/h)
Cooling Power	407 kW
Electrical Consumption	118 kW
COP	4,4
Refrigerant	R1233zd(E)

3.1.3. Environmental impact

Since the plant uses the heat supply about 8000h per year, about 6500 t of steam will be produced by the heat pump in the future with an electrical consumption of about 944 MWh yearly. This corresponds approximately to 4,1 GWh of thermal energy as steam. Assuming an efficiency of 85% in relation to the fuel input for a standard gas-fired steam boiler, approx. 4.8 GWh of natural gas will be saved. If a CO_2 emission factor of 0,201 t/MWh_gas [2] is taken as the basis for calculation, approx. 960 t CO_2 are avoided here. The exact CO_2 emission factor of the electricity used is not known. Different approaches can be used here.

1. CO_2 emission factor of CHP electricity (42% electrical efficiency) = 0,479 t/MWh_el.
2. CO_2 emission factor when changing the energy source to electricity = 0,366 t/MWh_el [3].
3. use of own electricity from the existing and planned PV systems + purchase of electricity from renewable sources = 0 t/MWh_el.

Thus, depending on the approach, the CO2 savings result in values between 508t and 960t savings per year.

Table 3: yearly CO2 savings

Electrical Energy Source	**CO_2 emission factor**	**Yearly CO_2 emission from electricity**	**Yearly CO_2 savings**
1 CHP produced	0,479 t/MWh_el	452 t	508 t
2 Change to electricity	0,366 t/MWh_el	345,5 t	614,5 t
3 Own + renewable electricity	0 t/MWh_el	0 t	960 t

3.2. Recycling industry

Recycling of used materials and raw materials is becoming increasingly important. More and more new processes for recycling waste are being developed and implemented on an industrial scale. In the following process, conventional household waste is converted into a high-quality thermoplastic composite material. For this purpose, household waste, previously considered non-recyclable, is taken and split into its basic components of lignin, cellulose, fibers and sugar in a complex process and then reassembled into a new matrix, the thermoplastic composite material. This is to be used in various applications in the future, e.g., for vehicle interiors.

One process step in the production is the drying of the material. Temperatures of around 130°C are required for this.

3.2.1. Boundaries

This project involves the construction of the first industrial application for the production of the new thermoplastic composite material. It was decided that the use of fossil fuel was not an alternative, so a comprehensive heat utilization concept was developed from the outset to bundle various waste heat streams and use them as a source for a high temperature heat pump. The concept includes various cooling and heating circuits at different temperature levels, all of which are interconnected.

3.2.2. Integration

The high temperature heat pump is the last link in a series of heat pumps providing thermal energy at different temperature levels. The schematic in Figure 6 shows only a very rough concept focusing on the different heat pumps. In addition to these heat pumps, there are several other thermal exchangers such as process heat exchangers or dry coolers for winter relief (delivering cooling water from cold outside temperatures instead of using the chiller) or even buffer storage. The circuit with the lowest temperature operates at 8°C and is used to cool various process steps. This temperature is generated by a chiller, which condensing heat is used in a water circuit at about 35°C. This level is used for cooling or heat recovery from warm material and exhaust air streams as well as for preheating material streams. It then serves as a source for a medium temperature heat pump that raises the temperature level to about 75°C-80°C. This level in turn serves as a source for various process steps, as well as a source for the high temperature heat pump. This then provides 130°C hot water for the drying processes. Approximately 1.5 MW of heating power is required for drying. Two heat pump systems, each with two independent refrigeration circuits, are used here, each with a thermal output of approx. 1 MW, so that only three of the installed refrigeration circuits are in operation at any one time and one circuit serves as redundancy or can cover power peaks in certain situations.

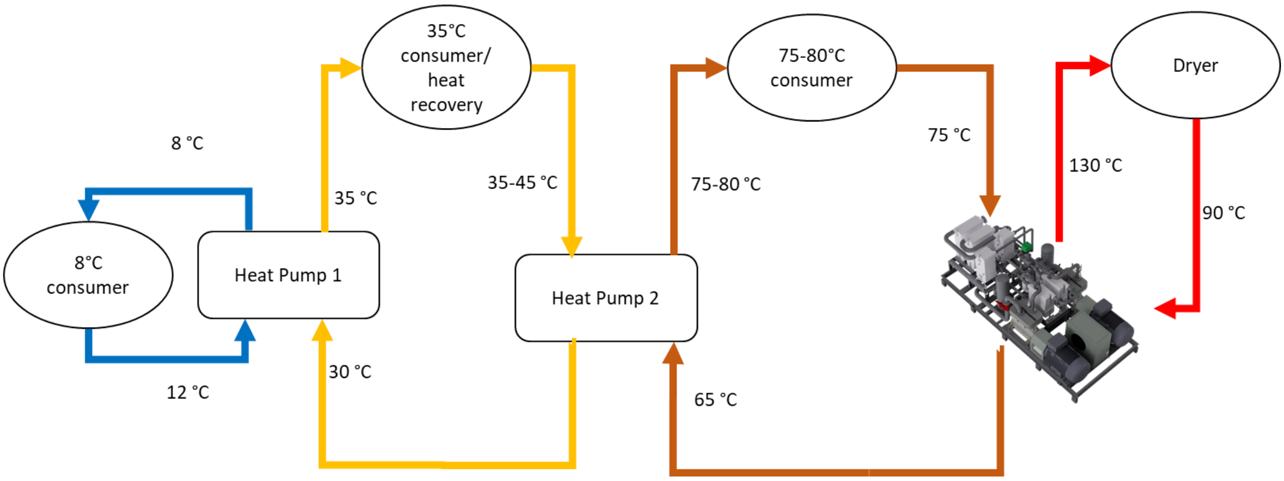

Fig. 6: thermal concept of the combination of cooling and heating circuits

3.2.3. High temperature heat pump system

Since this application does not use steam as a heat transfer medium, but hot water, the setup differs from the pilot system shown in chapter 2. Figure 7 shows the circuit diagram for the systems used.

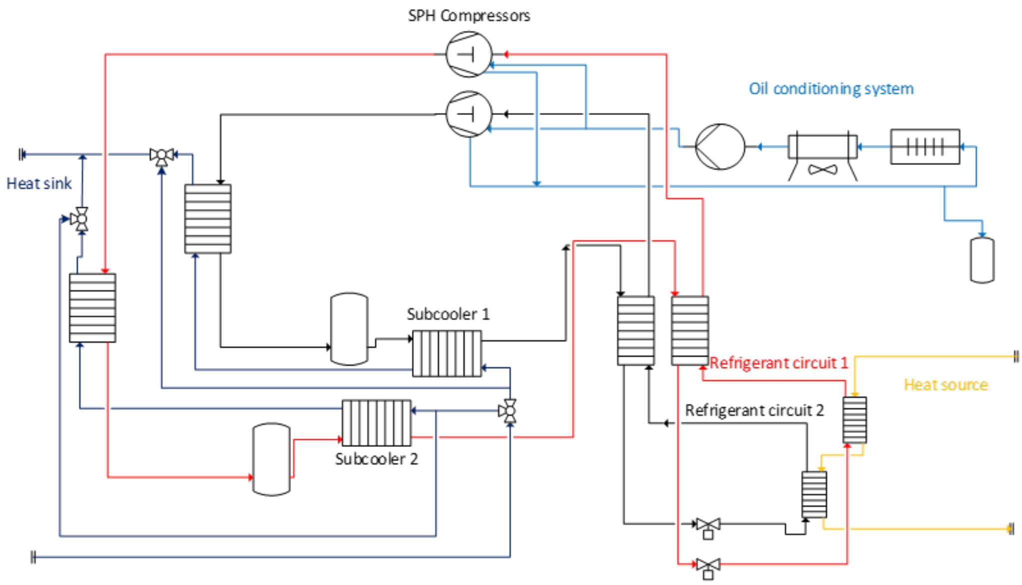

Fig. 7: P&ID 2 circuit hot water system

In the CAD model in Figure 8, you can see the compact design with the two compressors on the outside, condensers and subcoolers placed in between. At the other end are the evaporators connected in series and the internal heat exchangers. The design data applicable to this application can be found in Table 4. Because of the series-connected evaporators, the two refrigeration circuits operate at different evaporating pressure levels. In the first circuit, the evaporating temperature is about 67°C and in the second about 62°C. The condensing temperature, in turn, is very similar in both circuits at about 129°C. To make optimum use of the large spread in the heat sink, a subcooler was placed downstream of the condenser in each case to be able to subcool the refrigerant further and extract thermal energy. Due to the different evaporation temperatures od the two circuits, they don't have an identical power output. To be able to reach 130°C in each circuit a distribution valve is integrated between in the heat source water circuits. An additional distribution valve in each subpart of the water circuit helps to speed up the warm-up process if the complete water circuit is cold. In this case only a small part of the flow goes through the subcooler and condenser to reach higher refrigerant temperatures in the condenser. This helps in the warm up process due to higher temperatures in liquid part of the internal heat exchangers which then lead to higher superheat before the compressor and the possibility to go to higher evaporation temperatures earlier. In the case of water as a heat sink, the Lorenz COP (2) is often used instead of the Carnot COP to assess the efficiency of the system. Here, no individual temperatures of the process are used as reference, but the entropic mean temperatures are used.

$$COP_{Lorenz} = \frac{\hat{T}_H}{\hat{T}_H - \hat{T}_L} \tag{2}$$

The entropic mean temperatures are defined as follows.

$$\hat{T}_H = \frac{\Delta T_H}{\ln\left(\frac{T_{H,o}}{T_{H,i}}\right)} \qquad \hat{T}_C = \frac{\Delta T_C}{\ln\left(\frac{T_{C,i}}{T_{C,o}}\right)} \tag{3}$$

With T_H the temperatures on the heat sink side and T_C the temperatures on the heat source side.

In this application, the Lorenz COP is 9.6. With a designed and simulated COP of 4,4 for the high temperature lift from 75°C to 130°C, this means a Lorenz quality of approx. 46%. The system will be installed in the first half of 2023.

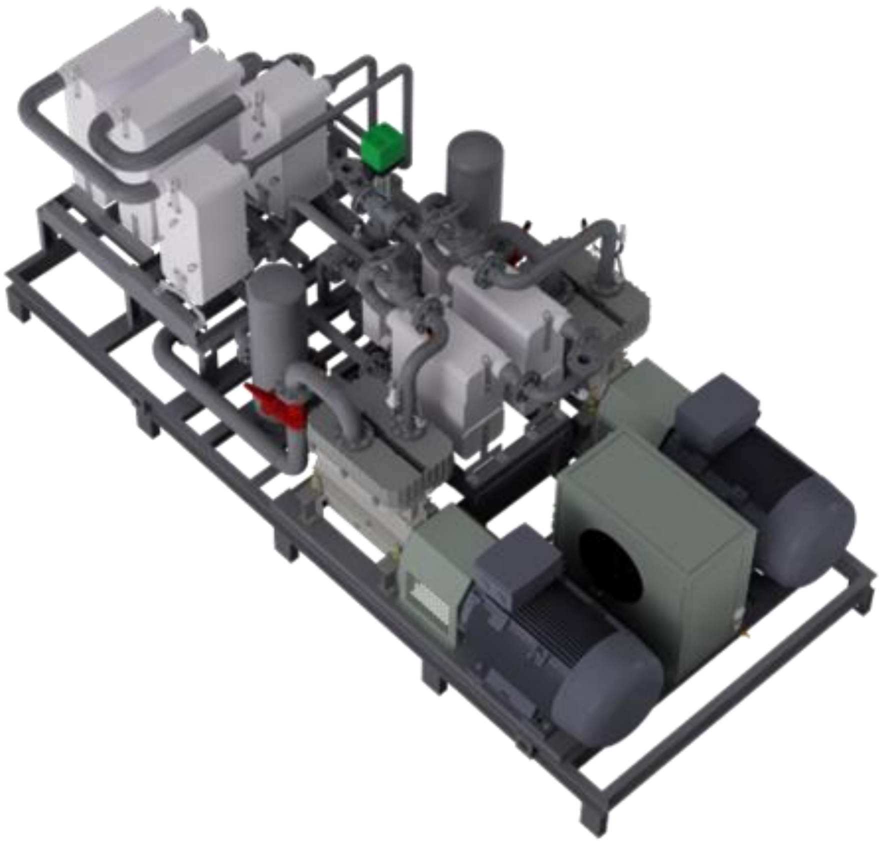

Fig. 8: CAD model of hot water system

Table 4: boundary conditions and simulated performance data for hot water heat pump

Parameter	**Value**
Heat Source Inlet	75°C
Heat Source Outlet	65°C
Heat Sink Inlet	90°C
Heat Sink Outlet	130°C
Thermal Output	1017 kW
Cooling Power	809 kW
Electrical Consumption	229 kW
COP	4,4
Refrigerant	R1233zd(E)

3.2.4. Environmental impact

With a planned annual service life of approx. 8000h, about 10.8 GWh of thermal process energy will be produced in the future. This corresponds to approx. 1.25 Mm³ of natural gas, which will not be required through the use of the heat pump. As the user consequently follows the principle of sustainability, only CO_2 neutral produced electricity is used in this project, so that approx. 2400 t CO_2 per year are avoided compared to a natural gas fired process heat production.

4. Summary

This paper shows the commercial availability of a high temperature heat pump system to produce steam and hot pressurized water in industrial applications. With current HFO fluids temperatures up to 165°C are possible. The system is based on a newly developed piston compressor, optimized for the use in high temperature heat pumps. The system is built as a standard compression cycle heat pump with internal heat exchanger.

The first application which will be delivered into the galantine production and produces steam at 2 bar abs (120°C) with using cooling water from CHP units at a level of 85°C/70°C. For this application a COP of 4,4 has been simulated. The second application is production of 130°C hot water for a drying process in the recycling industry. Here the heat source is given by the waste heat from chiller systems which are combined between 8°C up to 130°C. Here the last step of this cascade, the high temperature heat pump, reaches a COP of 4,4.

References

[1] European Commission, *2030 climate & energy framework*,Website of the European Commission, https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2030-climate-energy-framework_de, 9.2.2023

[2] Eurostat, *EU economy greenhouse gas emissions in Q2 2022*, WebsiteEurostat, https://ec.europa.eu/eurostat/de/, online data code: env_ac_aigg_q

[3] Bundesamt für Wirtschaft und Ausfuhrkontrolle der Bundesrepublik Deutschland, *Informationsblatt CO2-Faktoren*, Version 1.2, Stand 1.10.22