Developing a high-temperature heat pump technology concept using natural refrigerants

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High-temperature heat pumps show great potential for delivering process heat between 100 °C and 200 °C at high efficiencies compared to conventional boiler technology. Exploiting the potential and achieving the highest possible efficiencies for various applications requires various technical solutions. This article presents a technology portfolio based on the natural refrigerants CO_2, steam, and hydrocarbons and outlines the application potential through three representative case studies. A spray dryer for proteins, a brewery with a hot water requirement at 145 °C, and a dairy culture working with an inlet pressure of 8 bar steam were analyzed. The heat was supplied while reaching COPs between 2.02 and 4.93, ensuring efficient electrification.

Introduction

Heat pumps (HPs) are a key technology in the transition towards sustainable energy systems as they can provide electricity-based process heat at the highest efficiencies. High-temperature heat pumps (HTHPs) can be integrated into a variety of applications - both in existing plants and as part of new process equipment. Thereby, they contribute to the electrification and decarbonization of industrial process heat supply - helping end-users to achieve their climate targets while being economically competitive. This article looks at the potential of using natural refrigerants to cover a broad range of industrial applications at temperature levels up to 200 °C with a concise and cost-effective portfolio at high efficiencies.

High-temperature heat pumps for industrial applications

Exploiting the large implementation potential for high-temperature heat pumps for a variety of applications requires technologies which provide satisfying performances for a wide range of applications and can be provided at large scales.

To achieve adequate performance, there must be a good match between the temperature profiles of the process heat demands and the heat pump technology. This creates the need for the development of a concise portfolio of multiple future-proof technologies that cover a broad range of applications. While there is a variety of solutions for applications below 100 °C, there is a lack of viable solutions for higher temperatures.

Different processes require heat in diverse forms, such as steam, hot water, or hot air, and at different temperature profiles. Some processes require heat at a constant temperature and thereby have a low glide in the temperature profile, e.g., evaporation processes. In contrast, processes where a fluid is heated experience a large increase in temperature, such as drying processes. The type of working fluid, in combination with the system layout, defines the temperature profile of the HP system and the application potential of the respective working fluid to applications with a particular temperature glide.

Besides the proper integration and utilization of the HPs, using cost-effective equipment may decrease system costs. Existing equipment like compressors may be modified and optimized for higher temperatures, ensuring proper utilization of the existing knowledge with the technology enabling the benefit from existing production infrastructures.

A handful of refrigerants

Natural refrigerants are substances that can be found naturally occurring in the environment, with zero ozone depletion potential (ODP) and very low or zero global warming potential (GWP),They are readily available at a reasonable cost, are extensively researched, and cover a wide range of properties, providing a promising candidate for various applications.

The group of hydrocarbons covers a broad range of thermodynamic properties, suitable for a wide selection of operating regions. Longer hydrocarbon chains have a higher critical temperature allowing for high delivery temperatures in subcritical operation. However, equally higher normal boiling points potentially result in sub-atmospheric operation with low source temperatures. Hydrocarbons show little need for intercooling the compression process, even for large pressure ratios ensuring efficient compression. Hydrocarbon systems are expected to provide promising performances in applications with moderate-temperature glides like hot water production. Additionally, hydrocarbons show good miscibility with each other and may also be used as mixtures. However, hydrocarbons are flammable, which requires the implementation of certain safety measures.

R-718 (water) is well-known from steam systems and as a heat transfer fluid, ensuring commercially available components with high performance, such as turbo compressors. Water has a high heat of evaporation, enabling a large specific heat transfer rate, potentially yielding high COPs. However, low source temperatures

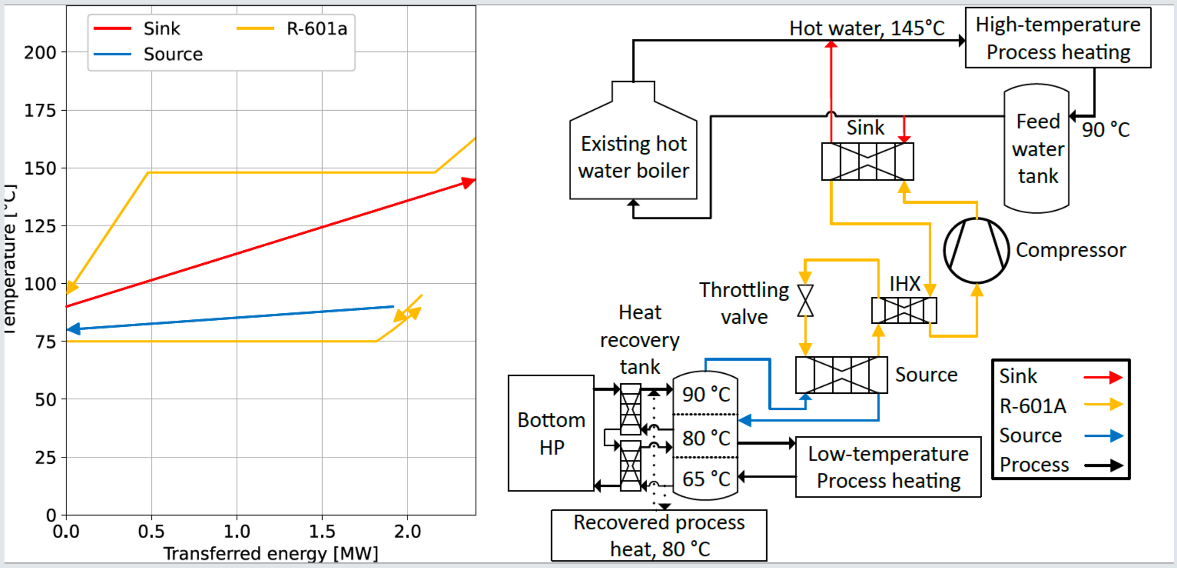

Figure 1a: Hot water system for a brewery.

Wort boiling with hot water system using R-601a from heat recovery tank

- A brewery uses 2.4 MW of hot water at 145 °C for wort boiling distributed several temporally offset batches in parallel. The remaining processes are covered by the heat recovery tank.
- Water returns from the high-temperature processes at 90 °C which is heated back up to 145 °C by the heat pump keeping the conventional gas boiler as a back-up.
- 90 °C hot water from the heat recovery tank supplies the heat pump and returns at 80 °C. The tank is supplied by a ammonia heat pump and recovered process heat.

Heating COP		4.93	
Heating capacity		2.4 MW	
Sink	Source	90 °C → 145 °C	90 °C → 80 °C
Refrigerant		Isopentane, R-601a	
Important remarks		COP of 2.49 w. bottom HP ATEX required	

Figure 1b: Hot water system for a brewery.

result in low densities yielding large volume flows. The R-718 systems are expected to provide the highest performances in applications with low-temperature glides like evaporation processes or steam production. Under certain circumstances, steam compression systems may also be a beneficial choice in larger temperature glide applications, although this might require systems operating with multiple pressure levels.

R-744 (CO2) is already a well-established refrigerant in the supermarket refrigeration sector and, more recently, for industrial HPs. R-744 has a low critical temperature, inducing high operating pressures in many applications, which yields high volumetric heating capacities lowering the investment costs due to more compact equipment. The R-744 system will mostly operate in the vapor phase resulting in no phase change of the refrigerant, hence no heat of evaporation. Therefore, it is intended for applications with large temperature glides like spray drying processes.

It might be appropriate to combine the technologies to mitigate their drawbacks, enhancing their strengths for applications with high-temperature lifts. This can be in cascade systems to produce steam using R-718 in the top cycle and a hydrocarbon in the bottom cycle, getting the high performance of R-718 without the large volume flow rates at sub-ambient pressures.

Commonly occurring industrial applications

To outline the application potential for the three technologies using hydrocarbons, steam, and CO_2, three potential application cases are presented, as they may be found in typical industrial processes.

Figure 1 (a, b) shows the application of a 2.4 MW hydrocarbon HTHP, which is integrated into a brewery with an existing hot water system and an ammonia HP. The HTHP consists of a single-stage HP with an internal heat exchanger (IHX) using R-601a (isopentane) as the refrigerant. The isentropic efficiency of the compressor is assumed to be 70 %, while the pinch temperature difference in all HEXs is 5 K. The HTHP delivers hot water at 145 °C, heating the return process water in parallel with the hot water boiler to ensure redundancy. The heat source at 90 °C is a stratified heat recovery tank supplying low-temperature processes with heat. This is done by an existing ammonia HP. The water is returned at 80 °C to the tank. The HTHP delivers hot water with a temperature glide of 55 K at a high COP of 4.93. The flammability

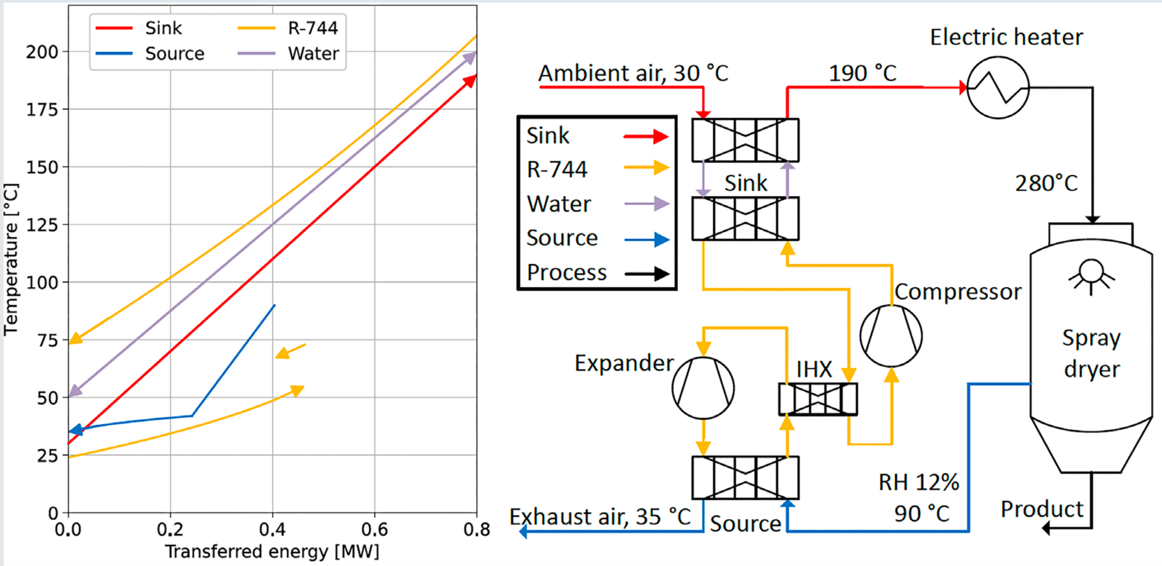

Figure 2a: Spray dryer for protein rich fish food production.

Drying of fish food at 280 °C in spray dryers using R-744 brayton heat pump

- A protein rich substance is dried in several parallel spray dryers using 15,000 kg/hr of dry air heated to 280 °C.
- Ambient air is heated from 30 °C to 190 °C in a heat exchanger connected to the heat pump by a secondary water loop before an electric heater raises the temperature to 280 °C w. a total COP of 1.77.
- The exhaust air comes out at 90 °C at 12 % relative humidity which is used as the source of the heat pump.

Heating COP		2.02	
Heating capacity		0.8 MW	
Sink	Source	30 °C → 190 °C	90 °C → 35 °C
Refrigerant		Carbon dioxide, R-744	
Important remarks		High pressures 150 bar Compact cycle	

Figure 2b: Spray dryer for protein rich fish food production.

of R-601a creates the need for an ATEX safety concept, which may be realized as a ventilated enclosure in the utility area of the plant. The presented setup is a suitable approach for the complete electrification of breweries.

A second case of an industrial site drying proteins in a spray dryer is presented in figure 2 (a, b). A protein-rich substance is dried using 15,000 kg/h of ambient air heated to 280 °C. The full gas cycle HTHP utilizes R-744 to heat the air to 190 °C through a secondary water loop before an electric heater delivers the remaining temperature rise. The pinch temperature difference in the air HEX is 10 K. The R-744 uses an IHX in addition to an expander with an isentropic efficiency of 30 %, delivering 0.8 MW heating using the exhaust air from the spray dryer as the heat source at 90 °C and a dew point of 42 °C. The temperature-heat load diagram shows a good match between the temperature profiles of the process heat demand and the R-744 resulting in a COP 2.02, which may be higher with more efficient compressors or expanders. Including the electric heater yields a system COP of 1.77

Steam is a common heat carrier in industrial facilities. The steam systems operate at different temperatures depending on the specific process requirements, but 4 bar to 10 bar are common in the food, pulp & paper, and chemical industry. A case with a cascade HTHP delivering 8 bar steam to a dairy culture production facility is presented in Figure 3 (a, b). The maximal consumption is 10.5 t/h of steam, which can be covered by a 6 MW HTHP. The steam is produced from the return condensate, which is pressurized to 8 bar before being evaporated in the sink. The chosen HP is a cascade system with a bottom cycle like for the brewery case, while a single-stage R-718 top cycle ensures the temperature lift from 120 °C to 170 °C. Liquid injection during the compression of R-718 mitigates excessive discharge temperatures. The local 70 °C district heating system is utilized as the heat source returning at 50 °C. The large evaporation heat of R-718 ensures a great temperature profile match with the steam and the bottom cycle. The IHX of the R-601a cycle yields the necessary superheating of the refrigerant, substantially improving the COP. In the suggested layout, the process steam is generated in a heat exchanger while condensing the steam from the HP cycle, which is preferred when there are high safety requirements for the purity of the steam. Steam could be provided directly from the compressor in an open loop cycle, which implies the risk of contamination with compressor oil (if present in the compressor) and might be more challenging to control for varying steam consumption. The cascade HTHP delivers the 8 bar steam with a

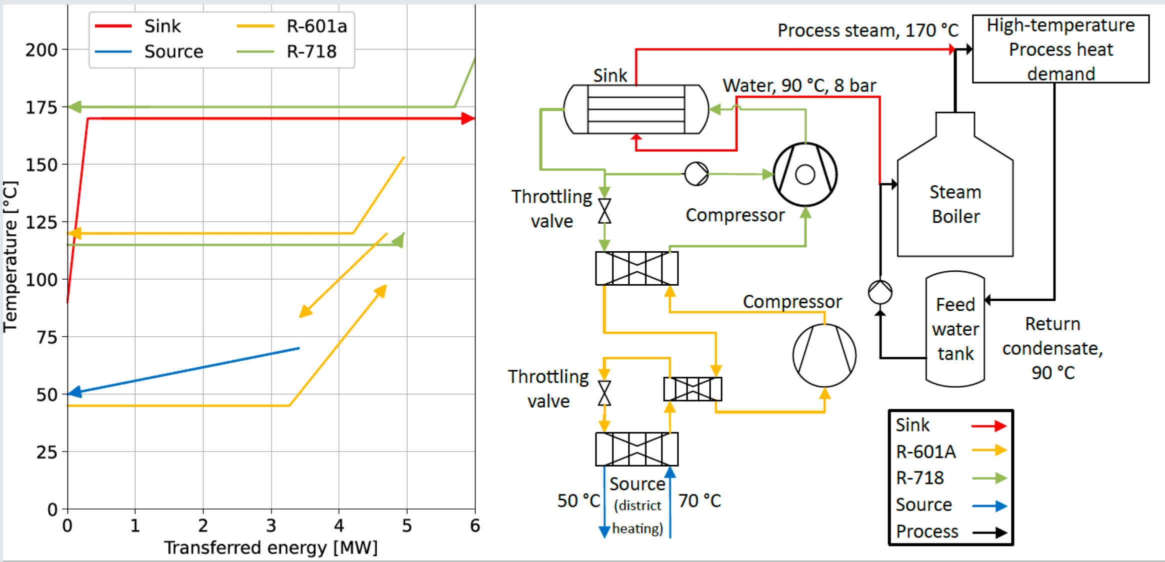

Figure 3a: Steam production from district heating for a dairy culture production facility.

Wort boiling with hot water system using R-601a from heat recovery tank

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Figure 3b: Steam production from district heating for a dairy culture production facility.

COP of 2.31.

The three different application concepts indicated technically promising cases for the three technologies, based on hydrocarbons, steam, and CO_2, and outlined their broad application potential for industrial process heating at highest performances. It may accordingly be derived that these technologies are representing a good basis for a portfolio of HTHPs based on natural refrigerants as currently being developed, tested, and demonstrated at large scales in the SuPrHeat project (http://www.suprheat.dk/).

Conclusions

High-temperature heat pumps can be implemented in a variety of industrial process applications, including existing plants and novel process equipment. The boundary conditions and performance may vary considerably depending on the application and require vastly different heat pump technologies to achieve the highest efficiency possible. This study indicates that using R-744, R-718, and hydrocarbons, it is possible to deliver process heat in the form of steam, hot water, or air at temperatures up to 190 °C with competitive COPs between 2.02 and 4.93. The three refrigerants exhibit fundamentally different thermodynamic properties, making them suitable for a broad range of applications with a concise, future-proof technology portfolio.

Acknowledgements

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