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HIGH TEMPERATURE HEAT PUMP APPLICATIONS FOR INDUSTRIAL PROCESSES

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ABSTRACT

As a result of continuous energy demand increase, while at the same time replacing fossil fuel boilers, decarbonizing the industrial process heat sector has never been more relevant. Heat pumps have great potential to support this journey. While the technology principles are not new, new applications and new process integration approaches are needed. This paper suggests solution examples for combined cooling and heating in F&B sites, including low pressure steam generation. New installations are discussed as well as refurbishments of existing systems. Simulations are used to give overview on COP as well as discuss installation costs. A couple of real projects are also given as examples in the field.

Keywords: Refrigeration, Industrial heat pump, Decarbonization, Process heating

1. INTRODUCTION

There are three megatrends which are challenging Industry's future energy supply:

Urbanization: growing population and results in higher energy demand. More food processing, more data centers, etc. The new energy demand must not come at a cost of air quality.

Climate change: fighting the climatic challenges by decarbonization is not new as a concept, in Europe already there are several working mechanisms, such as the European Green deal (EU-Council, 2023). Climate awareness has picked momentum also in business – global manufacturers have announced cutting on greenhouse gas emissions by 25% by 2030 compared to 2018, e.g. in (Meyer-Kirschner & Dorn, 2022)

Energy crisis: the war in Ukraine from 2022 has two major consequences for the energy sector. Firstly, natural gas price has been fluctuating > 50% in 2022. Secondly, due to insecurity in future supply of natural gas, Industry is very much focused on decoupling from it and replace gas boilers with alternatives, among others heat pumps. (Pachai, Hafner, & Arpagaus, 2023)

Target of this paper is to outline which heat pump technologies are relevant for high temperatures (> 100°C) based on system models on COP as well as give some examples of combined cooling and heating for industrial applications.

2. MAIN SECTION

2.1. Definition

When burning fossil fuels, it is easy to heat up the heat carrier to higher temperatures, since the flames burn with high temperature. Often process heat in F&B is designed for temperatures well above 100°C, often even 5 bar steam, even if real process need is below 100°C. (Hoffmann, 2023) HP operates differently: the performance of heat pumps is strongly dependant on the temperatures. Every 1 K increase of temperature decreases COP with 1,6% and decreases capacity with 0,3%. On the cold side: every 1 K increase in source temperature improves COP with 2% and capacity with 2% (Johnson Controls White Paper, 2023). These values are approximated and for only

NH_3, however the trend is universal. Thus, if possible, lower the temperature required for the process for optimal heat pump operation. However, in existing process sites this may be too expensive.

Significant amounts of industrial heat processes are < 100°C and addressable with already existing and mature heat pump technologies. However, the potential for heat pumps able to deliver heat sinks in the range 100°C – 200°C is at least two and a half times bigger, as seen in Figure 1 below:

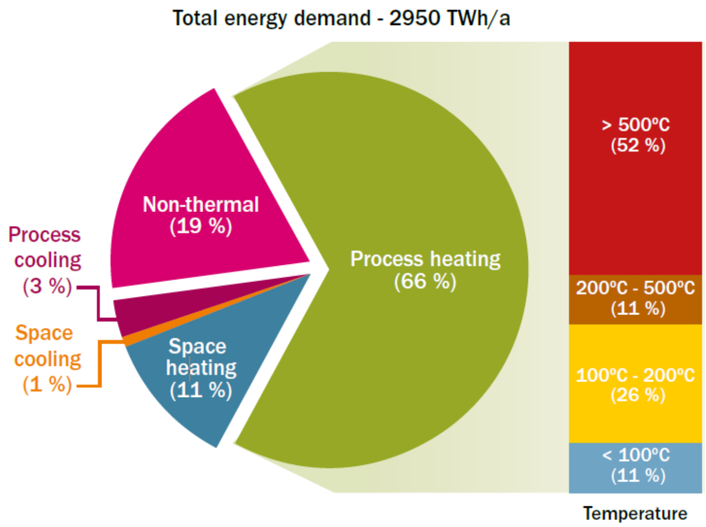

Figure 1: Breakdown of the final energy demand in European industry (EU28) by broad application (left) and process heating demand by temperature level (right) (Boer, et al., 2020)

According to the graph in Fig. 1 presented by (Boer, et al., 2020) the addressable heat demand for industrial processes < 100°C is around 11% from the total annual process heat in EU. For processes requiring 100°C – 200°C it is 26%. A total of 37%, corresponding to 723 TWh/year-equivalent of 85.000 MW heat from heat pumps, running 24/7 for a full year.

The potential is there, however next step is to understand the process heat requirement in industry, before selecting the most suitable heat pump technology and plan its system integration.

Table 1 below shows that with already proven and market available heat pump technologies < 100 °C a lot can be reached – practically (almost) everything for hot water for cleaning/washing and space heating. Heat sinks above 100 °C are still required to disconnect from fossils completely and some main sectors are again: Food & Beverages, Pulp & Paper, Chemicals. In these industries can be identified the main processes where a heat pump can be applied: drying, evaporating, boiling, pasteurizing, sterilization, distillation, etc.

Table 1: Overview of industry processes by temperature requirements (Arpagaus, Bless, Uhlmann, & Schiffmann, 2018)

Sector	Process	Temperature [°C]
Paper	Drying	90 - 240
	Boiling	110 - 180
	Bleaching	40 - 150
	De-inking	50 -70
Food & Beverages	Drying	40 -250
	Evaporation	40 -170
	Pasteurization	60 - 150
	Sterilization	100 - 140
	Boiling	70 - 120
	Distillation	40 - 100
	Blanching	60 - 90
	Scalding	50 - 90
	Concentration	60 -80
	Tempering	40 - 80
	Smoking	20 - 80
Chemicals	Distillation	100 - 300
	Compression	110 - 170
	Thermoforming	130 - 160
	Concentration	120 - 140
	Boiling	80 -110
	Bioreactions	20 - 60
Automotive	Resin molding	70 - 130
Metal	Drying	60 - 200
	Pickling	20 - 100
	Degreasing	20 - 100
	Electroplating	30 - 90
	Phosphating	30 - 90
	Chromating	20 - 80
	Purging	40 - 70
Plastic	Injection molding	90 - 300
	Pellets drying	40 - 150
	Preheating	50 - 70
Mechanical Engineering	Surface treatment	20 -120
	Cleaning	40 90
Textiles	Colouring	40 - 160
	Drying	60 - 130
	Washing	40 -110
	Bleaching	40 -100
Wood	Glueing	120 - 180
	Pressing	120 -170
	Drying	40 - 150
	Steaming	70 - 100
	Cooking	80 - 90
	Staining	50 - 80
	Pickling	40 - 70
Others	Hot water	20 - 110
	Preheating	20 - 100
	Washing/Cleaning	30 - 90
	Space heating	20 - 80

Technology Readiness Level (TRL) of Heat Pumps

- Conventional HP <80 °C, etablished in industry
- Commercially available HTHP 80-100 °C, key technology
- Prototaype status, technology development, HTHP 100-140 °C
- Laboratory scale research, functional models, proof of concept, HTHP >140 °C

To summarize, applications mapping for industrial processes where industrial heat pumps can be applied is not an easy task. Key takeaways from the available literature:

• With market available and proved heat pump technologies up to date (sinks < 100 °C) can be covered a considerable share applications for process heat.

• We can split industrial processes for high temperature heat pumps (sinks > 100 °C) in two steps: 1. 100 ~ 150 °C and 2. 150 ~ 200°C

• There is not a one clear industrial process demand split in the different sectors, but rather several sources with different results. It is crucial to investigate the concrete application in the industrial process and to challenge the process engineers to verify minimum viable temperatures.

• There are three main fields of application of high temperature heat pump for industrial processes:

Hot dry air (drying of milk for protein/milk powder, drying or preheating of foods, etc)

Hot water (cleaning of equipment, boiling/thermal treatment of product, washing bottles and tanks, pasteurizing, etc)

Steam (boiling/thermal treatment of product, pasteurizing, sterilizing of equipment)

2.2. Technology overview:

Prior to making a decision to install a heat pump in the factory, or what exactly type of heat pump is the best solution, a complete application mapping needs to be made and answer several key considerations:

Describe the processes heat demand – capacities, temperature levels, load profile

Describe the cooling demand, if applicable – capacities, temperature levels, load profile

Map the heat sources, if available – type, temperatures, characteristics (permanent or fluctuating)

Concurrence of cooling and heating

How much heat can be recovered from the refrigeration system and find the optimal heat source for the rest

Load profile of cooling and heating processes

Once we have the application mapping in place, a thorough review of all suitable technologies should be made. This paper focuses on examples of technologies for industrial cooling and heating applications in two tracks: new projects and refurbishment projects.

2.3. New projects process cooling & heating

A simple one-stage, as shown in Figure 2 below will rarely deliver both cooling and process heating with sinks > 100°C.

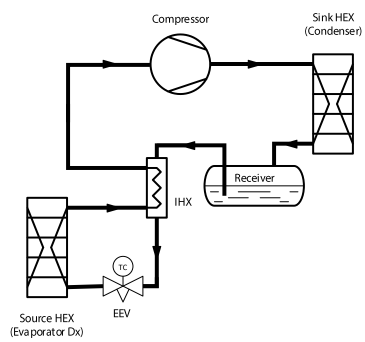

Figure 2: One-stage system

In industrial applications, such as Food and Beverage (F&B) processing, there are often two or more temperature levels of cooling, as well as multiple several sinks for heating processes. Building a new system allows refrigeration engineers to work closely with the process engineers and to understand the minimum viable requirements for process heating. Therefore, the design for the cooling and heating system can be made in a flexible manner, where two or more one-stage systems can be combined, each of which delivering the required temperature levels. These circuits may have different thermal capacities as well as different refrigerants, as optimal selection of the latter depends among others on specific saturated suction and condensation temperatures. It must be mentioned that at cascades there is a penalty in efficiency – as a rule of a thumb 5 K per cascade, but the flexibility of such designed system, proper selection of refrigerant for each circuit as well as reduced charge can be outweighing this efficiency loss.

Figure 3 below helps to understrand how to combine one-stage systems in cascades and which refrigerants can be used for each circuit.

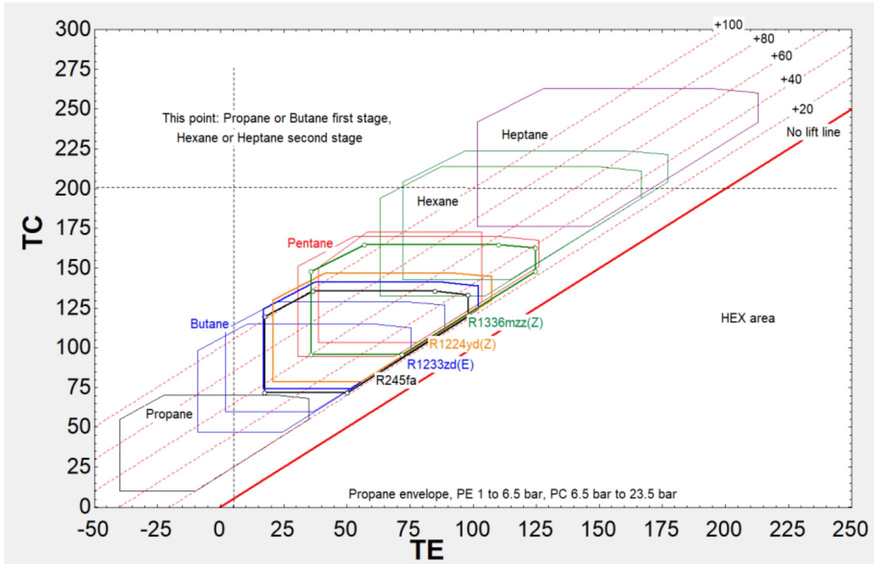

Figure 3: Combination selection one-stage systems in cascades

Using an internal simulation tool with integrated semi-hermetic piston compressors (Danfoss Bock, 2024), Figure 3 outlines how can multiple refrigerants – both hydrocarbons and synthetics, be combined in cascades for both cooling and different levels of process heat. Example: if the evaporating temperature is 5°C, and required condensing is 200°C, it is obvious that there is not one envelope covering both temperature levels. Therefore, we must split into two one-stage systems with a reasonable overlap of low cycle condensing and high cycle evaporating temperatures, which can be assumed to be 15-20K for reliable operation.

Next step is an efficiency simulation of the cycle. According to (Rangelov & Lund, 2024) Hydrocarbons can be used for a wide range of heat source levels. There is not one optimal refrigerant for all heat pump scenarios. Each refrigerant efficiency peaks depending on the specific process requirements, defined by sink and source temperatures as well as capacities. And while COP is important and first factor to evaluate, it is not everything. A Total cost of ownership (TCO) should be evaluated to make a conscious decision. A 2019 technical paper (Lund, Skovrup, & Holst, Comparing energy consumption and life cycle cost of industrial size refrigeraton systems, 2019) elaborates how complex a TCO evaluation is. Nevertheless, a pointer for initial investment can be given comparing swept volume per installed capacity. Even though it is not capitalized, it demonstrates difference in expected capital investment per technology: higher swept volume required results in bigger and/or more compressors, larger components and piping.

2.4. New project example

When a new system for process cooling and heating is built, and if refrigeration engineers need to work closely with the process engineers it is much easier to adjust system design to the precise process needs – temperatures, capacities, and source availability. It is a clear advantage to plan well as in this way the system can be designed in a flexible manner. One real life example of this approach shown in Figure 4 below.

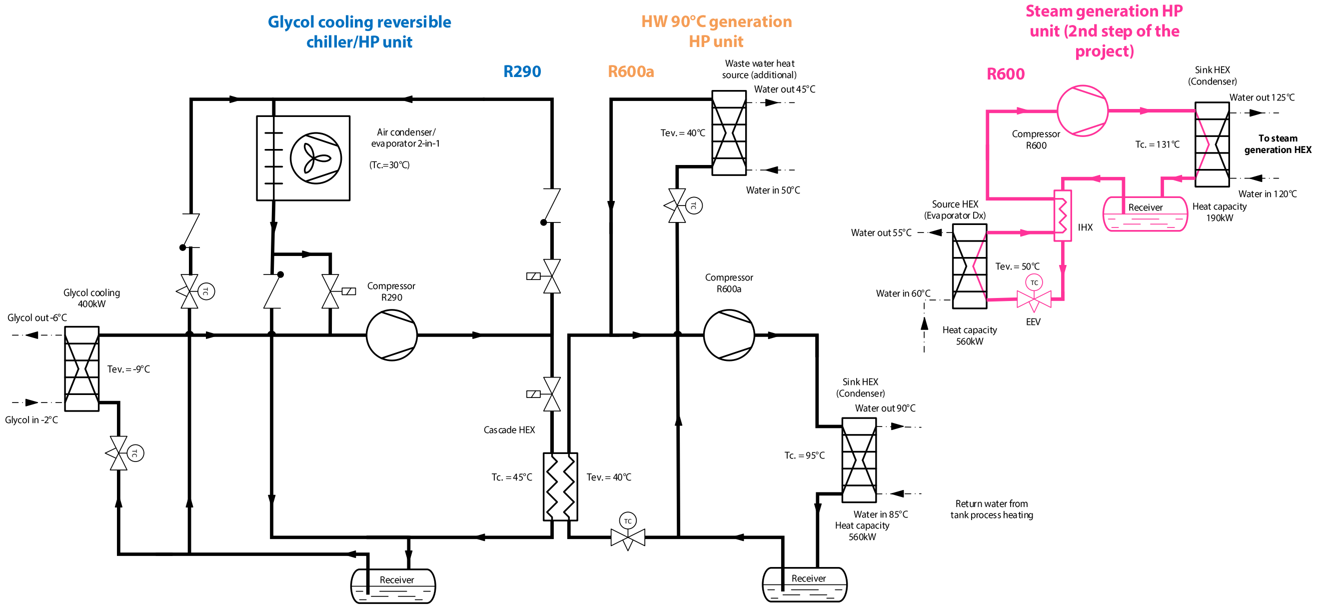

Figure 4: Combination of hydrocarbon one-stage systems for cooling and process heating in a Dutch brewery (Gulpener Bierbrouwerij, 2024)

The configuration in Figure 4 is a real-life example both cooling and process heating demands inclusive steam in a F&B plant – in this case a Brewery, can be entirely met with combination of hydrocarbon systems. Moreover, cooling and heating are completely decoupled from each other and with possibility to switch between heat sources.

• Cooling system (1st stage): glycol cooling to -6°C in a BPHE with a reversible R290 chiller/heat pump system. There is a 2-in-1 air condenser/evaporator unit to allow dual operation. There are 3 operation scenarios: cooling only, process heating only, simultaneous cooling and process heating.

• Hot water 90°C generation (2nd stage): On top of the 1st stage in a cascade there is a R600a HP system. Target is to deliver hot water for processing at 90°C with condensation in a BPHE at 95°C (sink). Source can be waste heat from the chiller (1st stage) when in operation, or waste heat from processes stored in a water tank. Both sources enable evaporation in the range of 40°C. Depends on availability it can be switched between both sources.

• Steam generation at 120°C (3rd stage): low pressure steam demand is met with a R600 heat pump, using source return water to the 2nd stage in the range of 70-80°C, and condensing at 131°C in a BPHE, which generates pressurized hot water at 125°C (sink). Downstream this line, there is a heat exchanger which generates steam at 120°C.

For this system were used semi-hermetic piston compressors type HG88e/3235/4 S HC (Danfoss Bock, 2024) in all circuits and already installed the 1st and 2nd stage and commissioned them in January 2024. The steam generating heat pump (3rd stage), which is second step of the project, will is installed in the first half of 2024.

2.5. Refurbishment projects for process cooling and heating

For many decades Cooling and process heating in industry have been disconnected from each other – the former by predominantly NH_3 industrial refrigeration (IRF) system and the covered by fossil fuels boilers. Decarbonizing and decoupling from fossil fuels can be done by combination of IRF system and a heat pump (HP). For the past decade, plenty of "add-on" NH_3 heat pumps have been installed in e.g. F&B industry on top of the IRF system. Lifting the waste heat from around 30°C to 80-90°C NH_3 can have a very high efficiency – COPs in the range of 5-6.

Nevertheless, there still will be some demand for low-pressure steam for F&B processes, and as of today NH_3, with some smaller exceptions, cannot cross the 100°C sink border line. Instead, a one-stage system with Hydrocarbons can be placed as a cascade on top of the existing NH_3, as suggested in Figure 5:

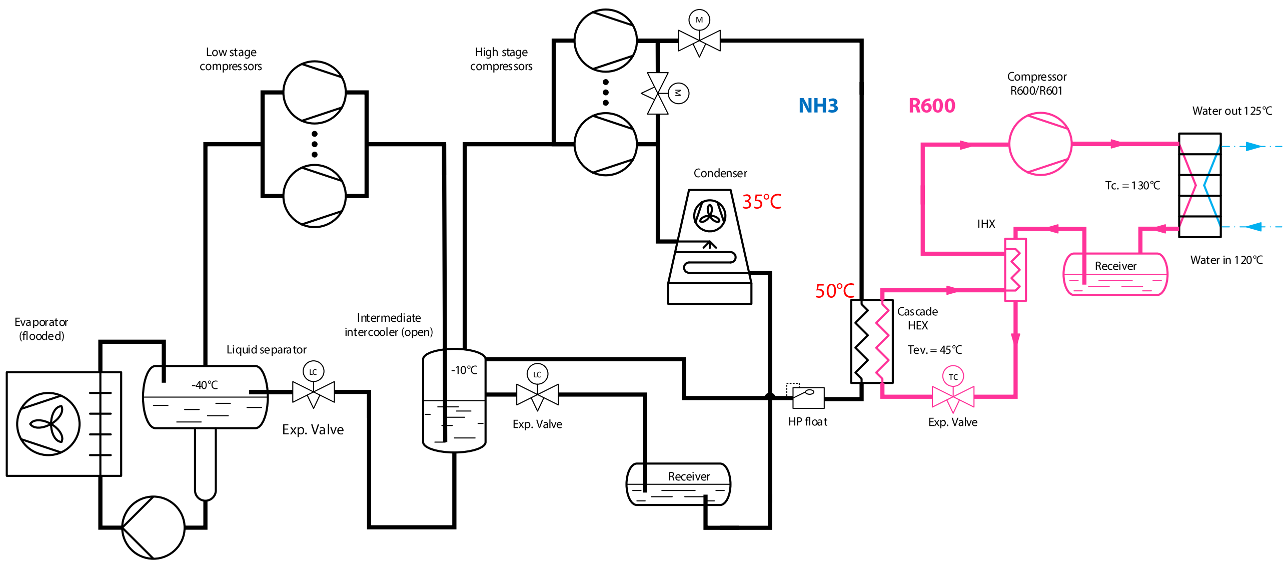

Figure 5: Add-on HP for steam generation on top of an existing NH_3 system

The layout in Figure 5 illustrates one possible solution for integration of a steam generating heat pump on top of an existing NH_3 two-stage typical industrial refrigeration system, which can be seen in most of the F&B plants.

• Cooling system: two-stage NH_3 with open intercooler (in this case), with two temperature levels: -40°C and -10°C, which can vary depending on the application. Waste heat is sent to an air-cooled condenser, and typical condensing design temperatures are approximately 35°C. This generic layout, with some variations, can be seen in multiple existing F&B applications globally.

• Process heating: one-stage Hydrocarbon (e.g. R600) system is on top of the NH_3 system, where the discharge of one (or more) of the high stage NH_3 compressors can be sent to a cascade heat exchanger, connected in parallel to the air-condenser. When there is demand from the process side, instead of all sending all the NH_3 hot gas to an air condenser, part of it is directed to the cascade HEX, which becomes a source for the high temperature unit. Sink is a BPHE, where the hydrocarbon refrigerant condenses, in this example, 130°C and heats up water up to 125°C. Downstream will be generated steam at 120°C, analogically to the example in the previous paragraph.

2.6. Refurbishment projects example

Usually, NH_3 systems are designed for condensing temperature in the range 30-35°C. However, this temperature level source could be too low to go to sinks at 120-130°C condensation. Several reasons: compressor envelope usually is not covering such high lifts in one stage; lubrication challenged – oils for high temperatures are often too viscous for lower temperatures; COP is not optimal due to too high lift. Therefore, during operation of the high temperature heat pump unit, unless an alternative heat source is available, the second stage of the NH_3 IRF system needs to elevate its condensation temperature up to values in the range of 40-50°C or higher. We should attribute the extra power consumption of the increased R717 condensing temperature to the penalty of running the heat pump, e.g. we should add the extra power to the heat pumps when evaluating the business case. This penalty can be minimized with adequate system integration. Typically, in F&B processes the demand of process heat for steam is significantly lower than the rejected heat from cold storage or freezing – therefore it is important to map the real demand and in case of several compressors on each NH_3 side, only the required amount need to elevate its pressure and not the entire NH_3 system – as suggested in Figure 5 above.

A typical example layout of a F&B process cooling 2-stage NH_3, with a possible steam generating heat pump add-on unit with Hydrocarbons is simulated to give some pointers on how such integration can be made optimal. It depends very much on existing system architecture and what is the optimal cascade temperature during different loads. Table 2 summarizes the assumptions for such a cascade of 2-stage NH_3 for cooling and a R600 system for process heating:

Table 2: Assumptions for simulation of system as per Figure 5:

Assumptions:	**Process cooling: NH_3 (2-stage)**	**Process heating: R600**
Condensing capacity, kW	1000	= (from 100% to 20% from NH_3 waste heat) + power use
Evaporating temperature, °C	-40/-10	$=T_{NH3\ cond} - 5$ K
*Condensing temperature, °C	35 to 50	130
Cascade HEX pinch, K	5	5
Superheat, K	0	10
Internal HEX efficiency	na	0,6
Other subcooling, K	2 K from condenser; open intercooler between stages	2 K
Compressor isentropic efficiency (ɳ)	0,7	0,7

**Reference scenario is based on $T_{NH_3\ cond}$=35 °C, and is being increased to 50 °C with 1 K steps*

Description:

Problem: Load of the IRF system (NH_3) is not the same as the heat pump (R600). The capacity of the former is typically larger, and the load is always present, even though (almost) never at full load but with variations depending on production load and season. While the capacity of the latter is expected to be smaller and load occurs when process heat is demanded – but not constantly. Therefore, it is very difficult to balance the loads

Purpose: to study and give some pointers how to evaluate system the condensing temperature of an existing IRF system (and hence cascade HEX temperature) as a function of the loads between the process cooling and heating systems

Methodology: The system in Figure 5 is simulated as per the assumptions in Table 2. The IRF system condensing temperature varies from the reference of 35 °C (standard) to 50 °C in steps of 1 K. Increasing $T_{NH_3\ cond}$, ammonia's COP decreases as the power use rises, and vice versa for the R600 heat pump – due to decreasing lift. It can be very complex to evaluate both systems COPs, therefore the study is performed with assumed fixed COP of the NH_3 system to the reference of condensing at 35 °C, and assume that any additional power use is due to the HP unit, so the additional power from the IRF system is added to the power consumption of the HP, hence its COP is penalized.

Results: In Figure 6 below

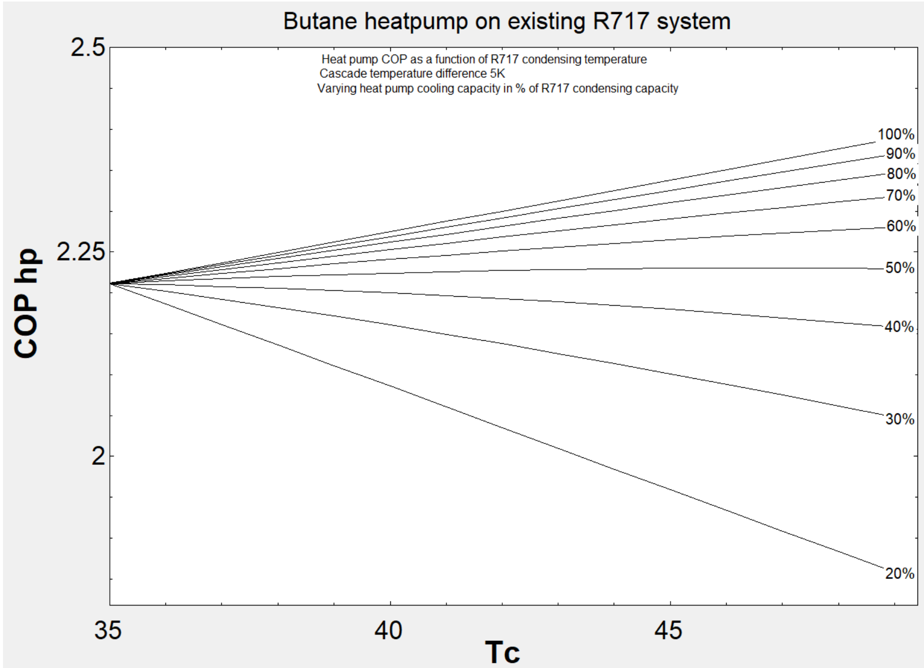

Figure 6: Add-on R600 COP_{HP} variation of elevated condensing temperature from the NH_3 (T_C) and utilized waste heat (%)

There always is a difference in the capacity of the heat pump and the existing cooling plant. If we elevate the condensing pressure of the entire IRF system but use much less of the condensing capacity for the HP unit, then there is large negative impact on the COP of the HP – because of its smaller size. The gains from increasing the HP's source temperature is smaller than the losses of increasing the condensing temperature. However, if we have a bigger size add-on heat pump, then there is a higher gain on the HP efficiency by increasing the cooling system's condensing pressure, and with a sufficiently large heat pump this might outweigh the penalty to the cooling system. Figure 6 summarizes the simulation results for modified COP_{HP} for utilizing condensing capacity from the bottom stage (NH_3) system from 100% (top line) to 20% (bottom line) with 10% steps.

What can be seen in the results in Figure 6 is that if there is a rather large heat pump unit "on top" of the cooling system, then it is worth it to elevate the condensing pressure as much as possible. But if it is a significantly smaller capacity, then it makes sense to keep T_C at a lower level. In this case based on the described system, the break-even point is when the HP utilizes around half of the condensing capacity of the cooling system – no significant changes in COP when increasing condensing pressure in the cascade HEX. Note: The results must be read in the context of this system layout with the assumptions made above.

Furthermore, these results are based on efficiency evaluation – which is the first factor which is evaluated, but also total costs of ownership must be studied. As (Rangelov & Lund, 2024) suggest it is a very complex task, but at least can be given an indication of initial investment with swept volumes of different cases. For this system layout and assumptions, the swept volume of the HP at Tc=35 °C is approximately 50% higher than if condensing pressure IRF system was at 50 °C, leading to bigger compressors, components and piping. This pointer is also important as a second step evaluating system scenarios.

To conclude, on the refurbishment of existing cooling systems with new high temperature heat pumps. It is possible to add a Hydrocarbon Heat Pump unit in cascade and generate steam. Proper system integration is a key, and one must study properly the existing system and how to balance the loads to have a maximum efficiency out of the heat pump. This must be done in conjunction with among others investment costs, and an indication can be given by swept volumes for each scenario. For a complete picture a total cost of ownership must be estimated.

3. CONCLUSIONS AND FUTURE WORK

Hydrocarbons are an extremely attractive solution in the whole spectrum of applications for cooling and heating, both as stand-alone systems and as add-on to existing refrigeration systems. First step is to generate low pressure steam, and with the current state of technologies 120 °C sinks are already market available and 140-150 °C are on the way. From cycle analysis perspective Hydrocarbons can be used efficiently up to sinks of at least 200°C, however some components and oils are currently challenged. These challenges are the same for every refrigerant, regardless of its chemical composition.

CO_2 and ammonia are typical in refrigeration and existing in many industrial refrigeration systems. Even though they already have reached (or soon will) their higher temperature limit, they can be successfully used in refrigeration and as a first stage of higher temperature heat pumps which generate steam. As a source for heat pumps CO_2 transcritical is not relevant because of its glide, while subcritical use (cascade) can be appropriate.

There are already several successful field examples for new projects in Industry (Food & Beverage) for new projects both cooling and process heating entirely with Hydrocarbons.

Refurbishment projects are more challenging to address, but again with the same technologies – Hydrocarbon system on top of an existing Industrial refrigeration plant low, pressure steam can be generated. For these cases proper system study and technology selection is a key for successful system integration and maximal efficiency.

As future work, the author is keen on a detailed study of the processes in real industrial sites to be performed and all source, sink levels, capacities and concurrence mapped. This demand data should be connected to the system calculations and hence link the most suitable technologies to each process. At a later stage also a more robust total cost of ownership evaluation needs to be performed and indications given.

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NOMENCLATURE

COP	Coefficient of performance	HP	Heat pump
COP_{HP}	COP of a heat pump	IHP	Industrial heat pump
COP_{HPmod}	Modified COP_{HP}	IRF	Industrial refrigeration system
T_c	Condensing temperature (°C)	F&B	Food and Beverage
$T_{NH_3\ cond}$	Condensing temperature NH_3 (°C)	HEX	Heat exchanger
NH_3	Ammonia (R717)	IHX	Internal heat exchanger
R600a	Isobutane	BPHE	Brazed plate heat exchanger
R600	Butane	EEV	Electronic expansion valve
CO_2	Carbon dioxide	TCO	Total costs of ownership

REFERENCES

Arpagaus, C., Bless, F., Uhlmann, M., & Schiffmann, J. (2018). *High temperature heat pumps: Market overview, state of the art,*. Energy.

Boer, R. d., Marina, A., Zühlsdorf, B., Arpagaus, C., Bantle, M., Wilk, V., . . . Benson, J. (2020). *Strengthening Industrial Heat Pump Innovation: Decarbonizing Industrial Heat.*

CHPA. (2023). *Industrial Heat Pump Development White Paper.* Heat Pump Committee of China Energy Conservation Association (CHPA).

Danfoss Bock. (2024, January 18). Retrieved from Danfoss Bock seme-hermetic compressors for stationary applications: https://vap.bock.de/stationaryapplication/Pages/Index.aspx

EU-Council. (2023, August 01). *European Green Deal*. Retrieved from https://www.consilium.europa.eu/en/: https://www.consilium.europa.eu/en/policies/green-deal/

Gulpener Bierbrouwerij. (2024, 02 21). Retrieved from https://www.gulpener.nl/heb-je-even/: https://www.gulpener.nl/heb-je-even/

Hoffmann, K. (2023). Economic benefit of 100K temperature lift with natural refrigerant. *10th IIR Conference: Ammonia and CO2 Refrigeration Technologies, Ohrid* (pp. 72-79). Ohrid: International Institute of Refrigeration.

IEA. (2022). *The Future of Heat Pumps.*

Johnson Controls White Paper. (2023). *Heat pump or boiler: what's the business case?* JCI.

Lund, T. (2023). Simulation tool for High temperature applications mapping. Danfoss.

Lund, T., Skovrup, M. J., & Holst, M. (2019). Comparing energy consumption and life cycle cost of industrial size refrigeraton systems. *Proceedings of the 25th IIR International Congress of Refrigeration.* Montreal: IRC.

Meyer-Kirschner, J., & Dorn, M. (2022). Towards energy transformation in chemical industry by largescale. *3rd High-Temperature Heat Pump Symposium 2022* (pp. 15-26). DTU.

Pachai, A., Hafner, A., & Arpagaus, C. (2023). High-temperature working fluids for heat pumps –. *10th Conference on Ammonia and CO2* (pp. 62-71). Ohrid: International Institut of Refrigeration.

Rangelov, I., & Lund, T. (2024). High Temperature Heat Pump mapping for Industrial applications. *High Temperature Heat Pump Symposium.* Copenhagen: DTI.

Reinholdt, L. (2023). TECHNICAL BUSINESS CASE BEHIND. *Køle- og varmepumpeforum 2023* (pp. 92-100). Copenhagen: DTI.

Servex. (2024, 02 21). Retrieved from https://www.servexkoelenvriestechniek.nl/: https://www.servexkoelenvriestechniek.nl/