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High Temperature Heat Pumps and New Technology

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Why you should attend

- To understand how ammonia–water hybrids and water vapour are reshaping high-temperature heat pump design, efficiency, and long-term regulatory stability.
- To learn the architectures that drive performance and explore multistage compression, desuperheating, economisation, subcooling and thermal buffering, and see how they collectively influence COP, reliability and industrial decarbonisation outcomes.
- To understand the growing role of water-based technologies and why they are becoming critical to next-generation industrial heat pump solutions.

Abstract

Industrial decarbonisation has driven a rapid shift toward high temperature heat pumps as an alternative to fossil fuel based boilers for generating hot water and steam. Achieving high efficiency in these systems requires appropriate refrigerant selection, stable heat source and heat sink integration, and correct application of thermodynamic principles. This paper presents a structured technical review of high temperature heat pump technology, focusing on ammonia–water hybrids and water vapour. Analysis is provided on system architectures such as multistage compression, desuperheating, subcooling, economisation and thermal buffering, which collectively determine the coefficient of performance (COP) and reliability. The findings indicate that natural refrigerants offer strong long term performance potential and regulatory stability. This paper aims to provide a good understanding of how water is playing a large part in the present and future of high temperature heat pumps by reviewing the two main technologies.

Keywords

High temperature heat pumps; industrial decarbonisation; refrigerants; ammonia; water vapour; thermodynamics; system design; Centrifugal; COP optimisation.

1. Introduction

Industrial heating has historically relied on fossil fuel powered boilers, with steam or high temperature high-pressure hot water distributed across sites for sterilisation, cooking, drying, washing, or space heating. As industries strive to reduce emissions and operating costs, attention has turned toward high temperature heat pumps as a technically feasible and energy efficient alternative. When correctly engineered, heat pumps can deliver large amounts of useful heat at high temperature while using less primary energy compared with direct electrical or gas-fired systems.

However, applying heat pumps successfully requires recognising that they are refrigeration systems, not boilers. Unlike boilers, heat pumps cannot tolerate unstable return temperatures, hydraulic shocks, poor buffering, or abrupt load swings. Many early failures often attributed to “bad heat pumps” were actually due to poor system integration and inadequate understanding of thermodynamic limits. Heat pumps operate within narrow temperature and pressure ranges, and deviations from these ranges degrade COP, accelerate compressor wear, and cause operational instability.

Refrigerant choice is equally important. Every refrigerant has distinct thermophysical properties, critical temperatures, operating pressures, and safety classifications that determine the achievable temperature lift and efficiency. High temperature industrial processes require refrigerants that can condense at elevated temperatures without excessive discharge pressures. This paper establishes a logical argument for the future of high temperature heat pumps.

2. Background and Refrigerant Selection

Firstly let us understand the options, charts 1 and 2 give a good indication of the limits of various refrigerants

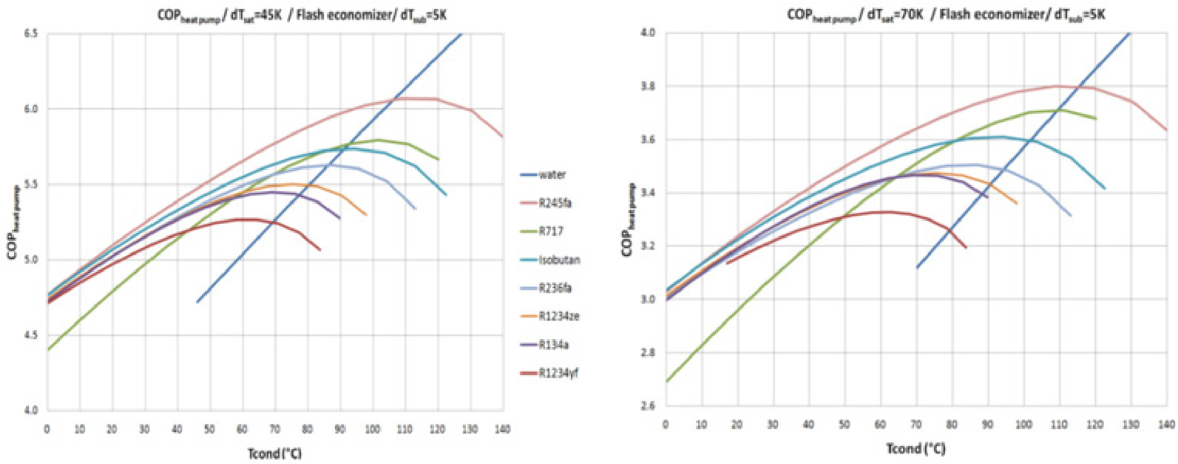

Figure 1 and 2: Refrigerant limits

The charts shown in Figure 1 and Figure 2 were compiled around 10 years ago and already we can see that all the synthetics shown apart from R1234ze have fallen by the wayside, CO_2 is not shown on this chart but only having a critical temperature of 31°C it becomes inefficient with high water return temps above the critical temperature. Natural refrigerants have a part to play in initially lifting poor grade heat sources to a usable level and for the second lift with high temperature heat pumps an ideal secondary fluid is water (R718). Water has a critical point of 374°C (221 bar-a). Water is also inert and has the advantage over other heat pumps in its usage of high temperature sources.

3. Ammonia–Water (R717/R718) Systems

Hybrid Heatpump technology

The combination of an absorption process and a vapour compression process with ammonia-water as working fluid gives a flexible heat pump system. A hybrid heat pump with a 50% mixture of ammonia and water, has the ability to heat water to over 100°C whilst remaining in the same pressure envelope of the compressor and rating of the equipment as purely using ammonia. The plant can cover extended temperature ranges over and above conventional heat pumps by using two combined industrial cooling processes.

Hybrid heat pumps (compression/absorption) exhibit interesting properties when compared to conventional vapour compression heat pumps. High heat sink temperatures can be achieved at the design pressures of standard refrigerating components. This is due to the boiling point elevation reached when mixing ammonia with water. The temperature glide of the ammonia-water mixture can be adjusted to the external heat sink/ source fluids by adjusting the composition. Changing the average composition of the solution circulating between the absorber and the desorber allows for a change in the saturation pressures in the system, and a capacity control as the compressor is supplied with lower or higher density vapour.

System Description.

Figure 3 shows a diagram of the hybrid heat pump system. The working cycle consists of a solution pump pumping solution rich in water from low pressure to higher pressure, and a compressor which is pressurising ammonia vapour from low pressure to high pressure. The solution rich in water is mixed with the ammonia vapour in the absorber, and heat is released to the heat sink during the ammonia absorption process. The resulting solution leaving the absorber is rich in ammonia, and is expanded to the low pressure side through the expansion valve before it enters the desorber. There, ammonia is evaporated out of the solution by heat extraction from the heat source, and the process repeats itself. A solution heat exchanger is installed for internal heat recovery and increases the cycle efficiency. Figure 4 shows the hybrid heat pump cycle components in a pressure, temperature, concentration (PTX) diagram.

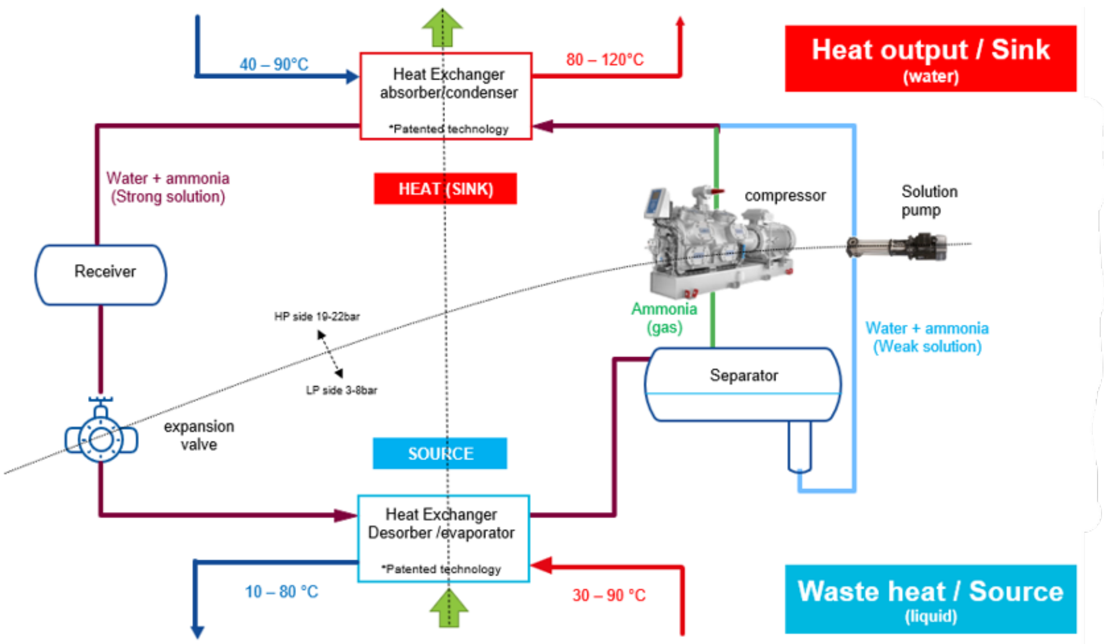

Figure 3: Hybrid heat pump sketch

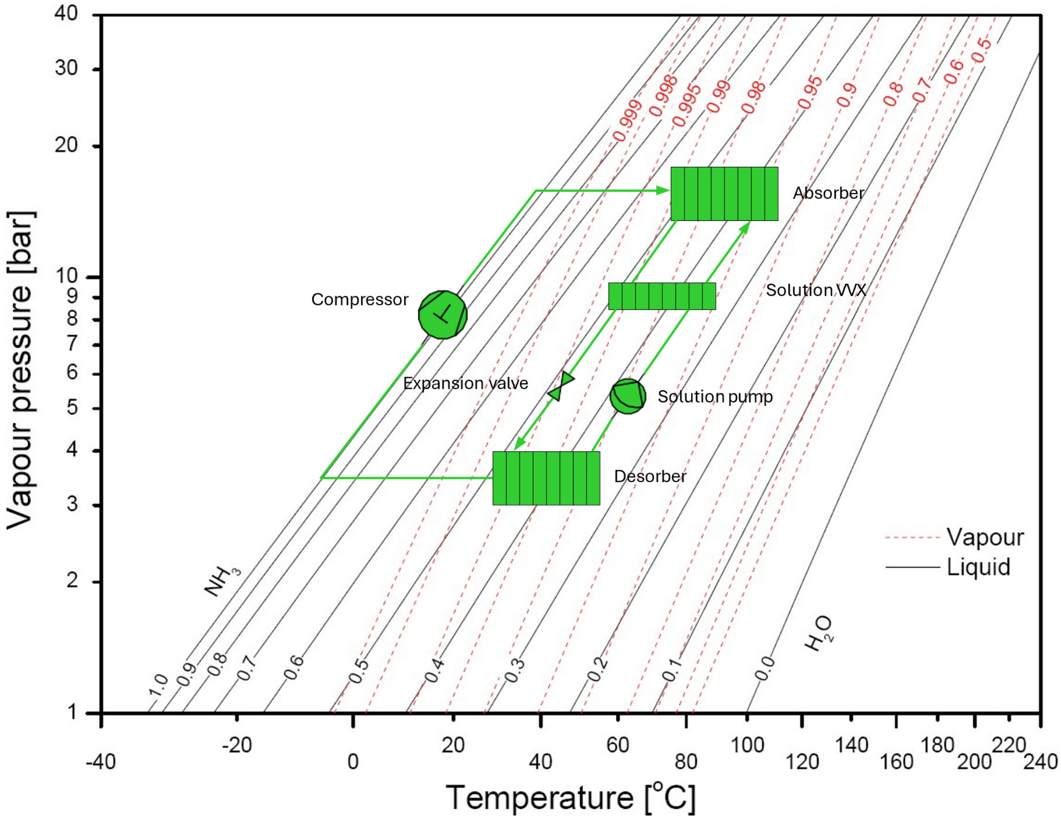

Figure 4: PTX diagram of ammonia-water mixture with hybrid heat pump components

The gliding temperatures of the working fluid mixture during heat extraction in the desorber and during heat release in the absorber can be an advantage in many processes. If the heat source is water that has to be cooled from 40 to 10°C, and the heat sink fluid is water that shall be heated from 50 to 90°C for example, the temperature glide of the working fluid mixture can be adapted to the temperature glide of the heat sink and heat source fluid. The compressor in the hybrid heat pump will then work against a lower temperature lift than the compressor in a conventional vapour compression heat pump using a single refrigerant which experiences a constant temperature during evaporation and condensation.

4. Case study: The Hybrid Heatpump System (HHS) at Tine Bergen.

- 2016 Consulting company requested advice on energy savings for a new dairy
- Existing system, stand-alone chillers and fossil fuel steam boiler.
- Hybrid Energy designed a complete chilling/heating/energy storage solution
- First, Tine wanted 102°C, but adjusted their heat exchangers/system to go to 95°C as the processes did not need 102°C
- Hybrid Energy got selected to deliver the complete system (Chillers, intermediate heat pumps, high temperature heat pump, electric heater and dry cooler, complete control system)
- 2019 Commissioning
- Good balance between heating/cooling needed
- Design was about 35% savings compared to company standard

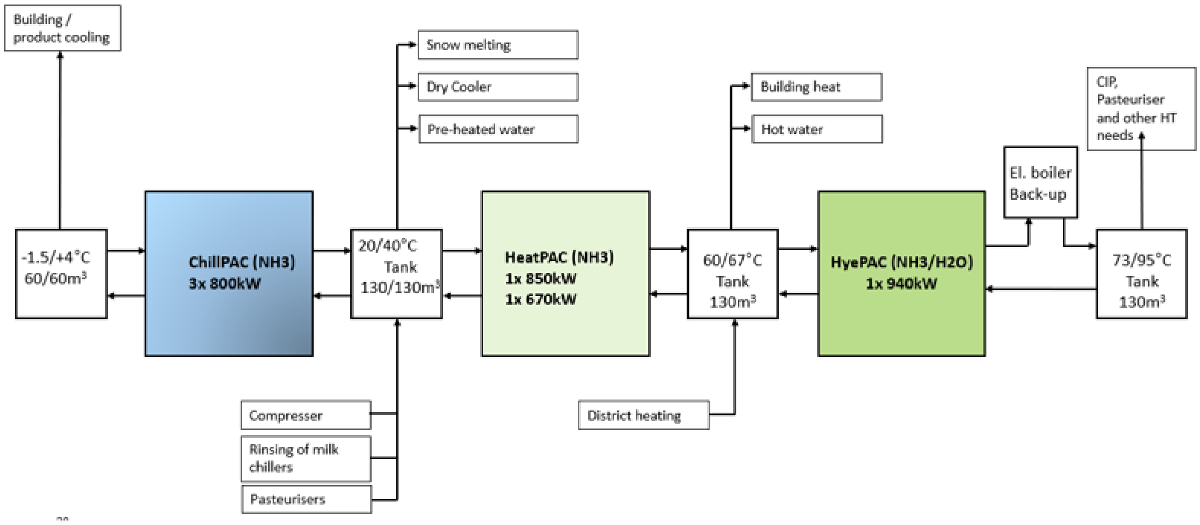

Figure 5: Energy efficient layout

During a winter test period (cloudy with snowfall) of 1 week from 10th Feb to 17th Feb 2020 we saw the following (Table 1).

System	Heat supply [MWh]	Power consumption [MWh]	COP
Chillers	70.4	16.7	4.2
NH_3 HP	105.9	20.1	5.3
HYBRID	69.2	11.7	5.9

Table 1: System performance

Results

The results of the conducted analysis are based on the investigated production week in February. The total amount of product was 733,957 L, corresponding to a production capacity of 88%, divided into 589,399 L of fluid milk (80.2%), 26,045 L of cream (3.5%) and 119,513 L of juice (16.3%). When comparing this amount to the total energy consumption of electricity (138.6 MWh) and DH (26.6 MWh), excluding the electricity generated by PV solar panels (0.8 MWh), this results in a specific energy consumption of 0.22 kWh l−1 product. The period studied covers one week in winter with temperatures below zero degree and snowfall, when energy consumption is generally higher than in summer. Therefore, it is expected that specific energy consumption will be reduced on an annual basis and full production volume. And despite the difficult conditions, the investigation already indicates a reduction of about 10% compared to the specific energy consumption of the replaced dairy, which was 0.24 kWh l−1 product on an annual basis. As the operational experience with this dairy is new, it is also expected that with increasing knowledge of process equipment and optimization techniques, the specific energy consumption will continue to decrease over time, thus reaching the targeted 0.15 kWh l−1 product on an annual basis. To identify potential improvements for the further reduction of the energy consumption, an energy and environmental analysis was performed, and the process integration and system performance investigated.Heating process at 95 was 22.3% of load, 67 was 17.3% of load and cooling 24% of load with a overall building energy demand load of 325.8MWh Energy source 56.5% Electricity, 0.3% PV, DH 10.8%, Waste heat 32.7%, chillers 28.7% and product 4%. Total energy source 245.5 MWh.

Based on the load percentages from the site test and by excluding the 20 °C processes, the total energy demand of the dairy is 315.9 MWh. The HHS requires an external energy input of 164.4 MWh to cover this demand, reduced by the 0.8 MWh of energy generated by the PV solar panels. For the reference system, the total energy consumption is 264.9 MWh, resulting in a total external energy saving for the HHS of 100.5 MWh (37.9%). Compared to the EB + DH scenario (using electric boiler and DH), this corresponds to electricity savings of 37.4 MWh (21.3%) and DH savings of 63.1 MWh (70.4%). In the NGB scenario, 98.7 MWh were provided by electricity and 166.1 MWh by the NGB.

Table 2. Comparison between the HHS and a reference energy system(separate Chilling and Heating).

		HHS		Reference	
Process	**Required [MWh]**	**Source**	**Amount [MWh]**	**Source**	**Amount [MWh]**
Heating at 95 °C	**72.7**	HYBRID	11.7	EB/NGB	76.5
		EB (electric boiler)	3.7		
Heating at 67 °C	**56.4**	NH3 HP	20.1	DH/NGB	59.4
		DH (district heating)	3.2		
Heating at 40 °C	**6.6**	Chillers	0	DH/NGB	6.9
Cooling 0.5/-1.5	**70.4**	Chillers	16.7	Chillers	12.3
Other	**109.8**	El. Grid	85.6	El. Grid	86.4
		El. Solar	0.8		
		DH	23.4	DH/NGB	23.4
Total	**315.9**		**164.4**		**264.9**
			NGB Natural Gas Boiler		

Conclusion for dairy case study

This study investigates the energy consumption and system performance of an integrated energy system of a green-field replacement dairy located in Bergen, Norway. The dairy features a novel and innovative solution of a fully integrated energy system. The system features high temperature heat pumps using natural refrigerants to provide all temperature levels of heating and cooling demands, enabling significant energy savings compared to the replaced dairy and other conventional dairy systems. By using available operation data for an energy-intensive week, an energy analysis has been performed to evaluate the system performance. The results were compared against reference dairy scenarios using conventional methods for providing the heating and cooling demands.

The results obtained show a specific energy consumption of 0.22 kWh l−1 product for the investigated week, allowing the integrated dairy to outperform the annual average of the replaced dairy despite challenging conditions. The energy analysis indicated that 33.0% of all energy sources in the new dairy already come from either waste heat recovery or solar energy, while the process achieves a waste heat recovery rate of over 95%.

By using the determined energy demand of the dairy for the week, the external energy consumption and GHG (green house gas) emissions for a corresponding reference system were calculated. The integrated dairy achieved external energy savings of up to 37.9%, while GHG emission reductions of 23.2% to 91.7% are achievable, depending on the respective scenario and case. The continuing trend towards an increasing share of renewable energy in the electricity mix has a positive effect on the competitiveness of the integrated system.

The detailed evaluation of the process integration revealed a good match between the heat supply from cooling processes and the heat demand from heating processes both in terms of overall load and the simultaneousness between supply and demand. Thermal storage tanks cover peak loads and provide useful heat storage, especially for the 95 °C circuit. A very modest use of backup resources in the process supports these findings, while further improvement potential was identified for the operation of these.

The results obtained clearly demonstrate that the integrated energy system with high temperature heat pumps and thermal storage tanks is suitable for providing all cooling and heating demands of the investigated dairy. The achieved performance values with a total system COP of 4.1 despite an energy-intensive operation period can certainly compete with conventional solutions. Thus, a further reduction of the specific energy consumption to the target value of 0.15 kWh l−1 product on an annual average appears feasible especially when you factor in the improved performance over a longer period considering various seasonal influences.

The original estimated saving were calculated at 37.5%; However, during the second year of operation overall savings were actually in the region of 40%!

5. Water Vapour (R718) Systems

When the condensing temperature exceeds 120°C, water vapour provides a much higher COP than all other fluids. It is however not used to date on heat pumps in closed circuit, but only in open cycle for "MVR" applications (Mechanical Vapour recompression), used in certain food processing or industrial applications, but with severe limitations on the available compression ratios. Water vapour requires large volumetric flows, and the existing compressor technologies (Roots compressors or blowers) do not make it possible to have simultaneously high flow rates, suitable compression ratio and acceptable efficiency.

Considering screw compressors, there is a choice of using dry or lubricated designs, but both have their drawbacks. Dry compressors require external synchronisation gears, and tend to have very low efficiency. The efficiency depends on low clearances between the screws, and between screws and housing, making these machines very sensitive to high discharge temperature. The reliability and performance of the system relies heavily on precise water injection in the screws to try to seal the mechanical clearance gaps, and to keep a precise control of the discharge temperature. In spite of attempts to optimise these systems, the efficiency of dry screw compressors tends to remain very low. Lubricated screws, on the other hand, have to face the challenge of lubrication at very high temperature in presence of water, and management of the oil in the system.

Centrifugal compressors are also unsuitable to compress water vapour. With the physical properties of water reaching the desired compression ratio requires either very high tip speeds of the impellers, or a multiplication of the number of impellers. But the combination of high speed and several impellers raises issues of rotor dynamics for the driveline.

The high discharge temperature raises problems of material choices for the impeller, to find the adequate combination between mechanical resistance at high temperature, light weight for good rotor dynamics, and manufacturability. In addition of course, the design of the impeller must be carefully optimised simultaneously for aerodynamic performance and mechanical resistance.

It is because of the complex interaction between all these parameters and constraints, that the technology of high speed motor with magnetic bearings was selected. Based on this choice, other technical challenges were the cooling of the motor, and the seal arrangements to avoid leaks of vapor into the motor or out of the circuit, or the inlet of air into the vapour circuit.

To satisfy all these constraints simultaneously, the key design features are:

- Synchronous permanent magnet motor
- Magnetic bearings
- 2 stage centrifugal compressor, one at each end of motor
- Intercooler between both stages
- Titanium impellers

Within YORK / Johnson Controls, magnetic bearings in water chillers were initially developed in the late 1990's for French nuclear submarines. The technology was later simplified and cost reduced for surface ships, with over 120 navy machines sold. Then, it was further developed and industrialised, to make it a standard land-based product called YMC² (York Magnetic Centrifugal Chiller), launched in 2011 and now sold worldwide with over 700 units built.

What was done within the scope of this study is to derive a high temperature water vapor compressor from the YMC² unit, by making the suitable modifications.

The solution was to mount the impeller directly at the end of a high speed motor rotating at the desired speed for the impeller(s) (figure 4 and 5). Most centrifugal compressors are single stage; but it is also possible to make two-stage compressors, with one impeller at each end of the shaft, or both impellers stacked at one end. As the motor is running at high speed, a Variable Frequency Drive (VSD) is needed to provide the required frequency to run the motor.

With high speed motors, various technologies can be used for the bearings: rolling elements, oil film, gas bearings. All these technologies have drawbacks and can present reliability issues. It was found that the best combination is to use magnetic bearings. In this technology, the shaft is magnetically levitated and is rotating without any mechanical contact.

Water (R718) is the ultimate natural refrigerant, offering an exceptionally high critical temperature (~374 °C) and very high latent heat. These properties make it uniquely capable of producing high temperature hot water and low pressure steam, up to approximately 160 °C depending on the compressor design.

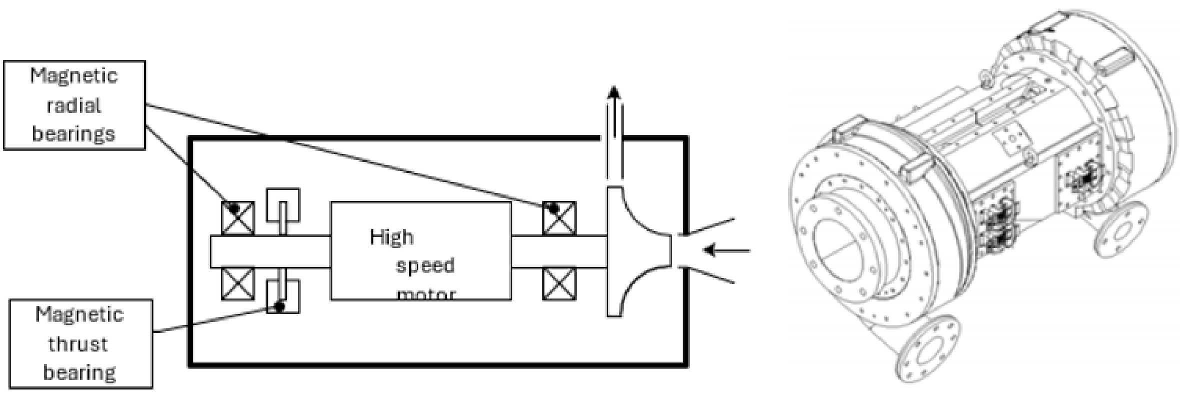

Figure 6 and 7: Magnetic bearing centrifugal compressor

6. Vapour Compression Architecture

Due to the fact that water vapour is very low in density, water vapour compression systems rely on high swept volume which brings into play the centrifugal compressors due to their high efficiency at full load plus the added advantage of no oil contamination into the steam generated. However, centrifugal compressors suffer from poor part load efficiency, which requires the system to be paired with energy stores and thermal buffers to maintain efficient operation.

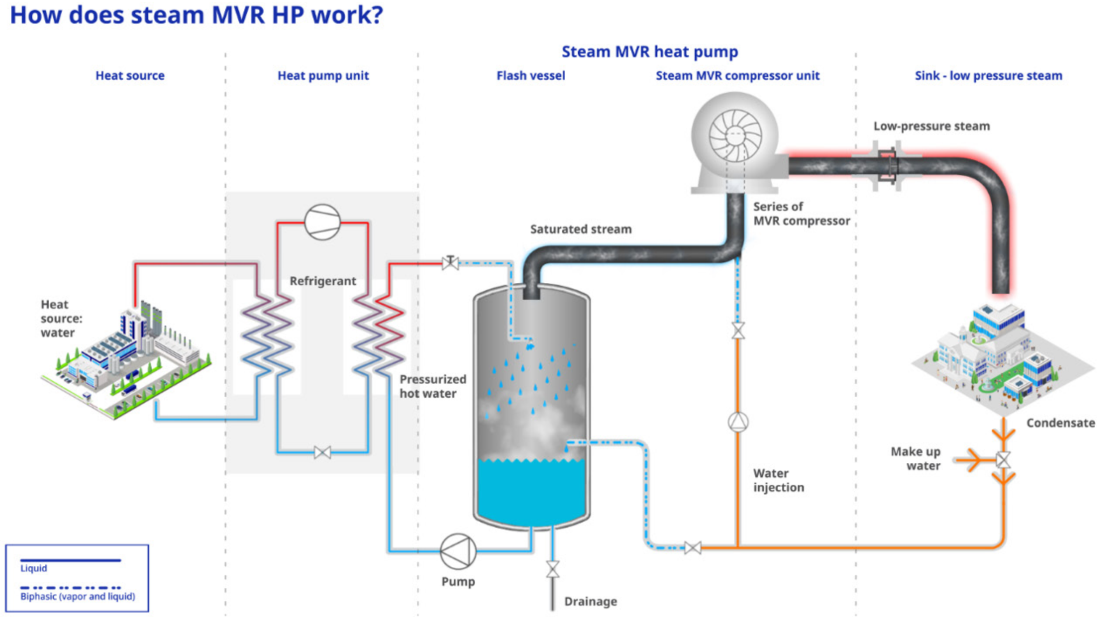

Figure 8: Basic MVR circuit

Operating Principle (Figure 6).

Water vapour heat pumps operate using a flash evaporation process

1. The heat source (water or another aqueous stream) enters a flash vessel.
2. The compressor draws a deep vacuum to reduce the boiling point of the source fluid.
3. Water vapour flashes off and is compressed to the desired saturation pressure.
4. The vapour condenses at the process producing hot water (condensate).
5. Condensate is returned as feedwater and water injection for desuperheating (compression efficiency).

This cycle is simple yet highly effective, with minimal heat exchange losses at the condenser due to the refrigerant and process fluid are the same substance.

Application Range

Water vapour systems can generate:

- ~144 °C steam at ~3 bar
- ~159 °C steam at ~5 bar

- High temperature hot water for industrial heating
- Lower pressure hot water for district energy network

MVR unit (single compressor version) and performance.

MVR unit

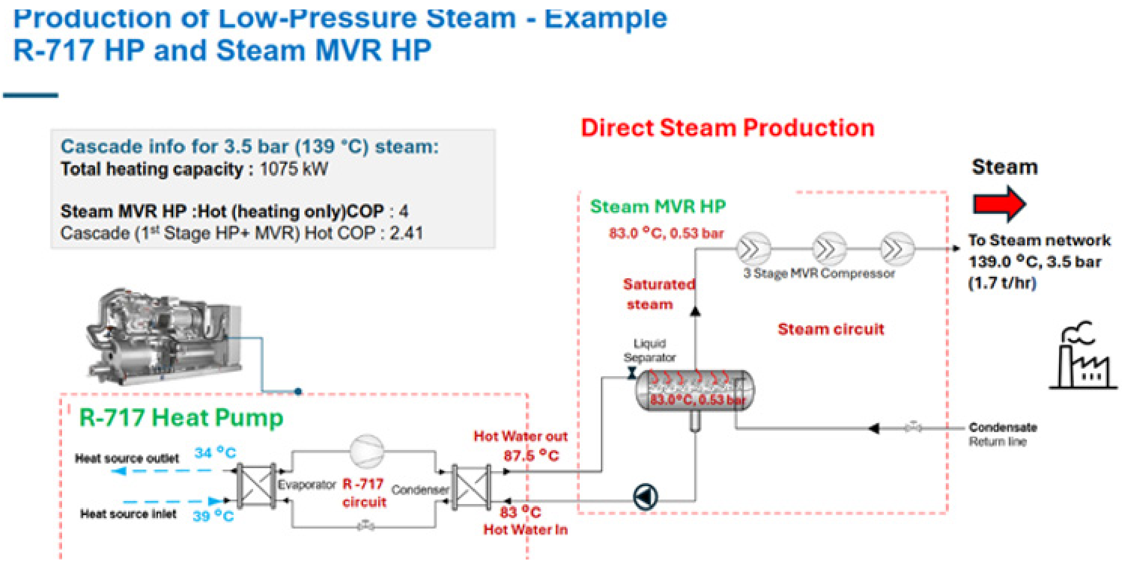

Figure 9: MVR circuit

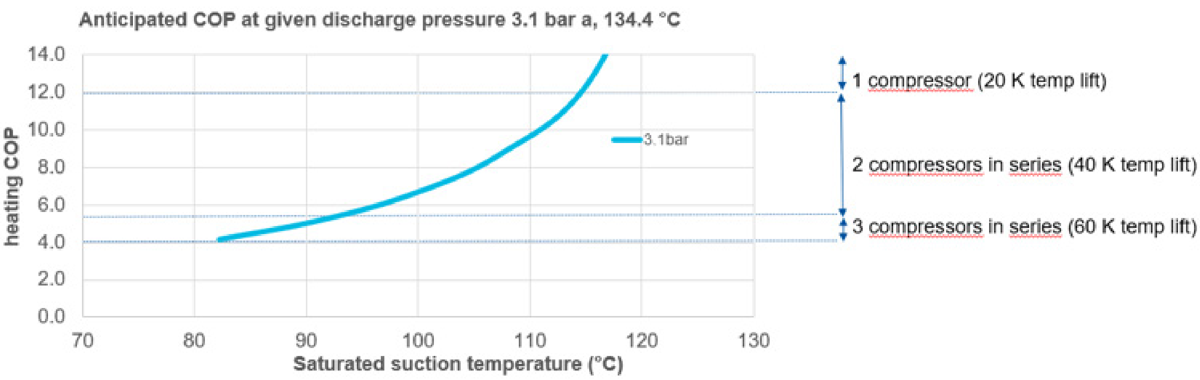

Figure 10: Compressors needed

MVR Conclusion

A water vapor centrifugal compressor on magnetic bearings has been developed, suitable for operating conditions 90/140°C evaporation / condensation. A prototype was successfully tested in a Mechanical Vapour recompression system. The potential for industrial applications looks quite promising. Among other possibilities, this machine can regenerate low pressure vapour at 140°C from waste heat at 90°, which seems of high interest to potential users. The design is based on heavy-duty industrial technology, suitable for highly service-critical applications. The range of compressors is designed around a series of four motors already existing. Machines will have the option of multiple compression stages, depending on the application, with a heating capacity ranging from 500 kW to about 9 MW.

The use of water vapour for this application is very attractive because it is totally benign to the environment. But most of all, it is clearly the right fluid for the application, irrespective of any other consideration.

7. Final Conclusions

High temperature heat pumps provide a technically robust and energy efficient pathway for industrial decarbonisation when correctly designed and applied. Their performance depends on several interconnected factors: refrigerant thermodynamic properties, system architecture, source and sink temperature stability, and the correct selection of compressors, heat exchangers, and control strategies. Across all technology classes reviewed in this paper, the dominant influence on system efficiency remains the temperature lift between the heat source and heat sink. Systems with stable, high temperature sources and moderate lifts consistently achieve superior COP.

Both the water/NH_3 and water vapour systems have the advantage of using very high source temperatures, for example from a district heating system or high temperature waste heat plant.

Water vapour, with its extremely high critical temperature and benign safety profile, represents the ultimate natural refrigerant for very high temperature applications, especially where steam production is required.

Beyond refrigerant selection, system design plays a decisive role in determining performance. Thermal buffering, multistage compression, desuperheating, subcooling, economisation, and precise control of evaporator and condenser temperature differences all have significant influence on achievable COP. Compressor selection must account for part load characteristics and long term maintenance considerations. When these principles are applied holistically, high temperature heat pumps can deliver reliable and efficient performance while reducing reliance on fossil fuel based heating.

Industry practitioners must consider lifetime cost of ownership, refrigerant environmental profile, site specific safety requirements, and process heat demands when choosing a solution. The long history and strong technical fundamentals of natural refrigerants suggest that they will form the backbone of industrial high temperature heat pump technologies for decades to come. As regulatory, environmental, and energy cost pressures increase, correctly engineered high temperature heat pumps provide a compelling route toward resilient, low carbon industrial heating.

Developments in the field of very high temperature heat pumps and vapour compression are opening doors where the technology previously just did not exist. It is expected to provide great energy savings in the future.

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About the author

After graduating in mechanical engineering with a bias in refrigeration design, Brian Gaughan FInstR started his career in commercial refrigeration making his way through to industrial refrigeration design; for the last 14 years he has focused on plant energy efficiency leading into working with various heat pump technologies.