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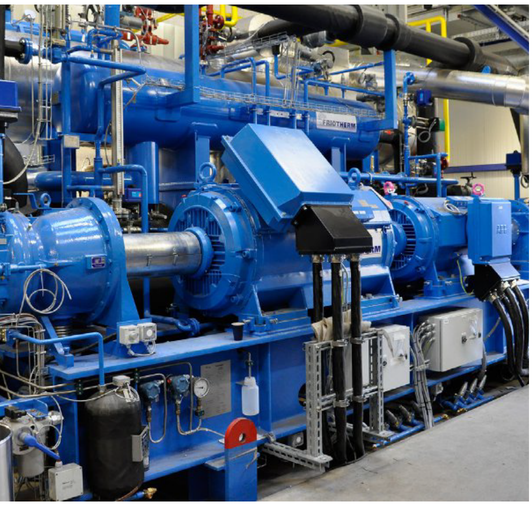
HIGH-TEMPERATURE HEAT PUMPS FOR INDUSTRIAL APPLICATIONS



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45th Informatory Note on Refrigeration Technologies

“High-temperature heat pumps are a key technology in the decarbonisation of process industries.”

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Summary

High-temperature heat pumps (HTHPs) are a prime option for harnessing the huge energy potential of waste heat in processing industries, improving their energy efficiency and reducing their carbon footprint. The HTHP market is dominated by vapour compression technology, but few equipment of this type are capable of delivering heat at temperature levels (over 90 ° C) compatible with the needs of the food, chemical and paper industries in particular. Current research and development activities are therefore focused on technologies and working fluids adapted to these needs. Absorption heat transformers and absorption-compression heat pumps are the most promising solutions in this respect.

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Introduction

Industrial heat consumption accounts for about 20% of total global energy consumption and the vast majority of it is obtained from the combustion of fossil fuels (IEA, 2018). Hence, each year, it is the main source of direct industrial CO_2 emissions, representing 24% of global CO_2 emissions in 2018 (8.5 $GtCO_2$) (IEA, 2020). Industries need to reduce their carbon footprint to be in line with countries' future carbon budgets set by international agreements such as the COP 21 (UNFCCC, 2015). Industries therefore have a strong need for sustainable energy transition via implementing energy efficiency measures and replacing fossil fuel sources by low-carbon and renewable technologies.

In most process industries, there is a lot of waste heat that is a by-product of industrial processes. This waste heat is available freely or at the cost of discharging it to the environment through cooling towers. A significant amount of this waste heat is at low-temperature and cannot be reused in other processes. Globally, an estimated 42% of industrial waste heat is available at temperatures below 100°C (Forman et al., 2016). However, thermal processes requiring heat supply between 80°C and 300°C are common in various industrial sectors, including agro-food, beverage, chemical, and paper industries. For instance, Figure 1 illustrates an annual process heat demand up to 200°C in different EU industrial sectors (total amount of 730 TWh per annum).

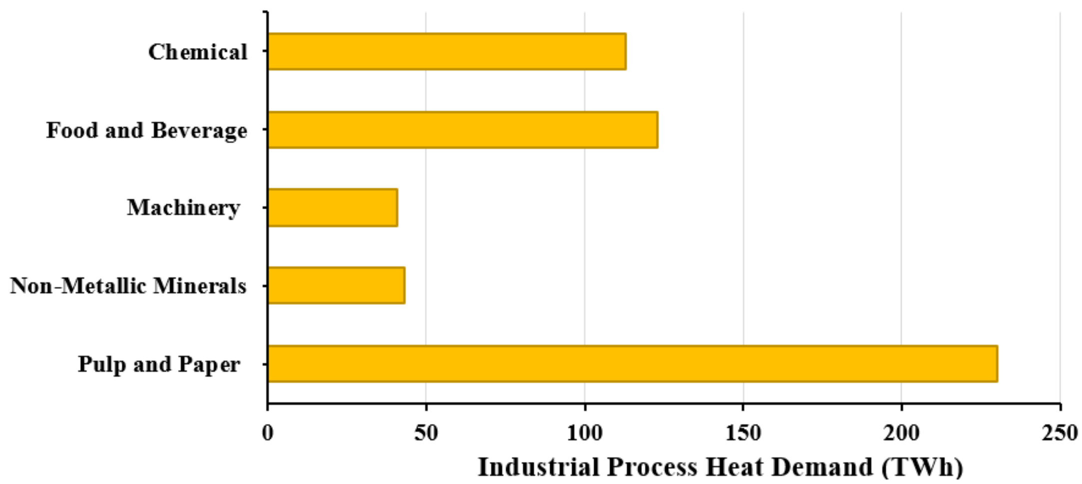


Figure 1: Process heat demand up to 200°C in EU industry by sector (de Boer et al., 2020)

The integration of high-temperature heat demand and the availability of low-temperature waste heat within an industrial plant (or in close vicinity) provides an opportunity to use a heat pump to increase the efficiency of energy utilisation in the whole plant (e.g. in Figure 2). Therefore, high-temperature heat pumps (HTHPs) will be a key technology for such a sustainable energy transition in industries.

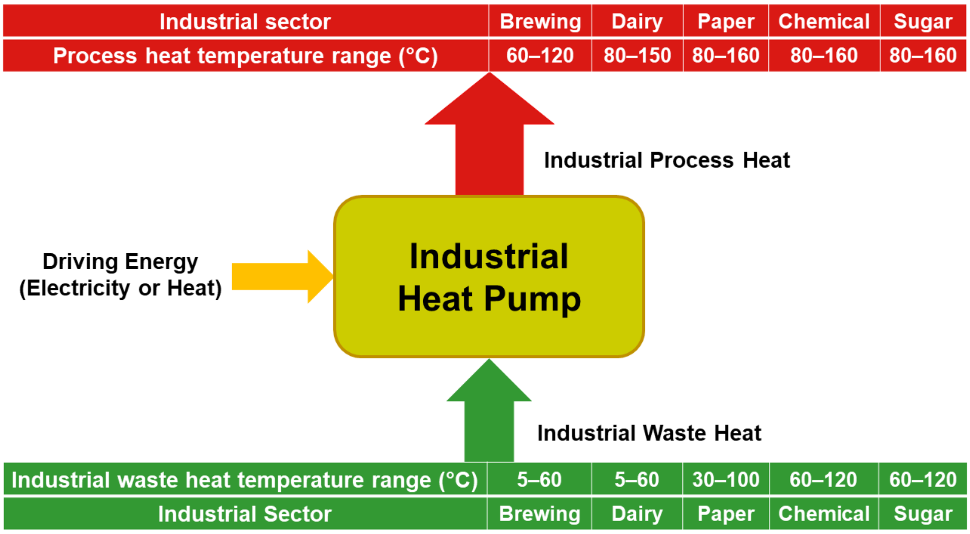


Figure 2: Industrial waste heat recycling using high-temperature heat pumps

HTHP technologies are classified mainly into two types: work-driven and heat-driven heat pumps. Work-driven heat pumps include the standard vapour compression heat pump (VCHP) technology and the more recent compression heat pump with solution circuit, which is also referred to as absorption-compression heat pump (ACHP).

Moreover, in industries where steam is used as a heat carrier, or where there is an excess of steam as in drying processes (Bantle, 2018), heat pumps can also be employed very efficiently together with mechanical vapour recompression (MVR) to reach high temperatures. This technology has long been used in industry. For instance, Lazzarin describes in (Lazzarin, 2007) that one of the very first heat pumps in the world was built in 1855 by Peter Ritter von Rittinger, and that he was already using MVR to compress vapour developed in aqueous solution concentrators from a temperature of 117°C till 300 kPa (at which the condensation temperature is 138°C). Nowadays, MVR is employed in different industrial processes, such as heat recovery from high-boiling solvents, or steam from drying processes, by removing the vapour/steam evaporated from the product and compressing it to provide the heat source for the evaporator. MVR is a proven technology in process plants to upgrade the quality of surplus (waste) low-pressure steam (below 5 bar) in order to reuse it in the plant. Current steam MVR systems operate in the heat source and sink temperature range of 50–140°C and 50–180°C, respectively (Spoelstra et al., 2017). The heating capacity of these steam MVR systems can reach 60 MW with a COP in the range of 3.5–10. Such systems are energetically and environmentally attractive; they reduce primary energy consumption and CO_2 emissions. However, among other factors, the economic competitiveness of this technology is highly dependent on the system's heating capacity, which is above 10 MW based on currently available steam compressor technologies (Elmegaard et al., 2017; Bantle et al., 2019).

Among heat-driven heat pumps, the absorption heat pump (Type I, AHP) and the absorption heat transformer (Type II, AHT) are relatively the most widely known and commercialised technologies. Although there have been many advances in heat pump technologies and their deployment in the residential sector, to date much less progress has been made in the industrial sector.

Ideal performance

Heat pumps operate at two temperature levels (work-driven heat pumps, e.g. VCHP and ACHP) or at three temperature levels in the case of heat-driven heat pumps (e.g., AHP and AHT) as illustrated in Figure 3. The highest theoretical performance (i.e. ideal performance) of this type of heat pump technologies is represented by the corresponding ideal/reversible heat pumps (e.g. Carnot heat pump).

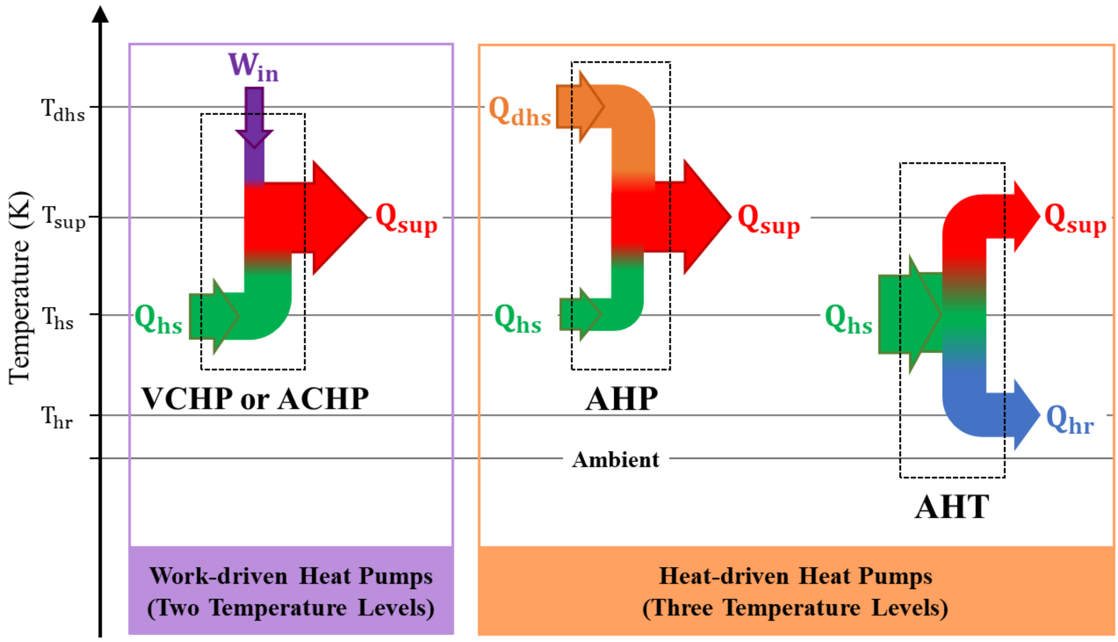


Figure 3: Different types of heat pumps. Note: dhs=driving heat source, hs=heat source, hr=heat rejection medium, in=input,Q=heat flow, sup=heat supply,W=workflow (electricity)

The performance of such heat pumps is given by the Coefficient of Performance (COP), defined as the ratio between the heat supplied (i.e. Q_{sup}) and the driving energy consumed (electricity, W_{in} , for work-driven heat pumps and heat, Q_{dhs} or Q_{hs}, in other heat pumps): $COP_{VCHP\ or\ ACHP}=Q_{sup}/W_{in}$,$COP_{AHP}=Q_{sup}/Q_{dhs}$, and $COP_{AHT}=Q_{sup}/Q_{hs}$ .Table1 and Table 2 show the ideal COP values of the work- and heat-driven heat pumps, respectively, as a function of the source, supply, driving heat (only for the AHP), and reject heat (only for the AHT) temperatures. Temperature lift is also another key indicator for assessing the performance of the heat pump, which is defined as the difference between the temperatures of heat supply and source (i.e. Temperature lift=T_{sup}-T_{hs}). In Table 2, the ideal COP of AHT (Type II heat pump) is calculated at a typical heat rejection temperature of 25°C.

Temperature (°C)	40		60		80	
90	50	7.3	30	12.1	10	36.3
100	60	6.2	40	9.3	20	18.7
120	80	4.9	60	6.6	40	9.8
140	100	4.1	80	5.2	60	6.9
160	120	3.6	100	4.3	80	5.4

Legend: Temperature Lift (K) COP (-) Heat Source Heat Supply

Table 1: Ideal COP and temperature lift of work-driven heat pump as a function of heat source and supply temperatures.

In all types of heat pumps (Table 1 and Table 2), an increase in the temperature lift is at the expense of reducing the heat pump COP. A higher COP is obtained with a higher heat source temperature. As can be seen in Tables 1 and 2, the COP of the heat transformer is the most dependant on the heat source temperature.

Type	Absorption Heat Pump (AHP)									Absorption Heat Transformer (AHT)					
Temperature (°C)	40			60			80			40		60		80	
90	155	50	2.0	135	30	2.2	115	10	3.3	50	0.27	30	0.59	10	0.87
100	175	60	1.9	155	40	2.1	135	20	2.5	60	0.24	40	0.52	20	0.77
120	215	80	1.8	195	60	1.9	175	40	2.1	80	0.20	60	0.43	40	0.64
140	255	100	1.7	235	80	1.8	215	60	1.9	100	0.17	80	0.38	60	0.56
160	295	120	1.6	275	100	1.7	255	80	1.8	120	0.15	100	0.34	80	0.50

Legend: Temperature Lift (K) COP (-) Driving Heat Temperature (°C) Heat Source Heat Supply

Table 2: Ideal COPs and temperature lift of heat-driven heat pumps as a function of heat source, heat supply, and driving heat (in case of AHP) temperatures. Note: the temperature of heat rejection medium of AHT is set at 25°C.

The actual COPs of work- and heat-driven heat pumps are lower than the ideal COPs presented in Table 1 and Table 2, due to the losses/irreversibilities inherent in the processes involved in heat pump technologies. The ratio of actual-to-ideal COPs (COP_{actual}/COP_{ideal}) is a useful indicator for comparing the efficiency of different types of heat pump technologies, and it indicates the level of potential for efficiency improvements. Thereby, depending on the heat pump technology, this ratio (COP_{actual}/COP_{ideal}) can be estimated as follows, under typical operating conditions:

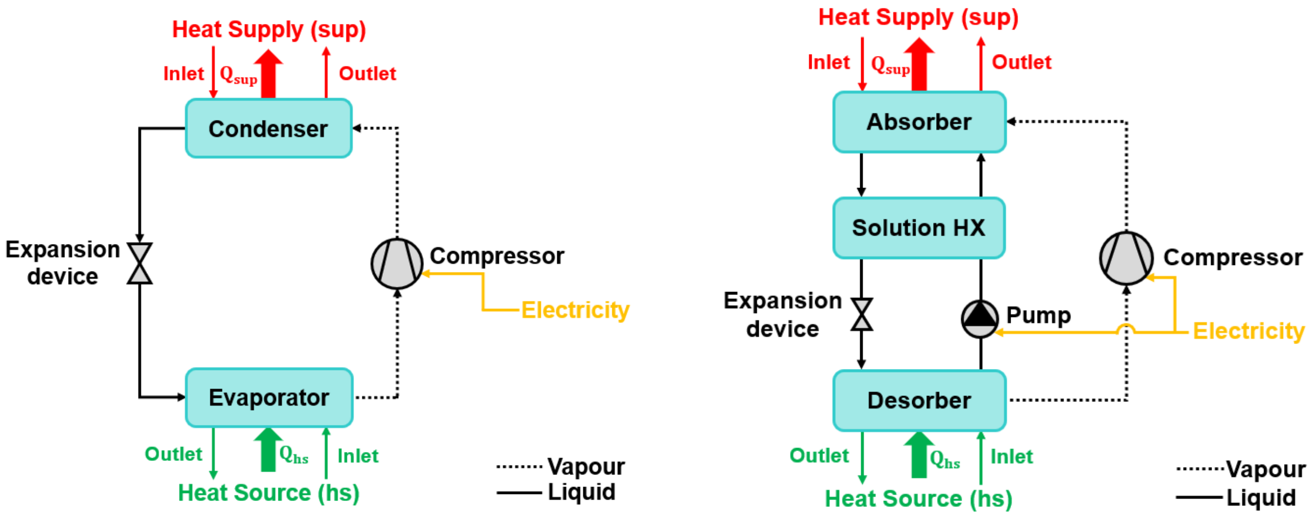
- 45-55% for vapour compression heat pumps;
- 40-51% for ammonia/water absorption-compression heat pumps in temperature lift of 22–65 K with heat source/sink temperature gliding of 27/25–18/65°C;
- 52–64% for single-stage LiBr/water absorption heat pumps;
- 51–77% for single-stage LiBr/water absorption heat transformer technologies.

HTHP systems and technologies

WORK-DRIVEN HEAT PUMPS

The VCHP technology, based on a mechanical vapour compression process, is the most extensively developed and marketed heat pumping option. A comprehensive review on the current status of HTHPs based on this technology is presented in Arpagaus et al. (2018). This technology uses varieties of configurations, including single-stage VCHP with and without internal heat recuperator (Figure 4(a)), VCHP with multi-stage compression processes, and cascaded single-stage VCHPs with different working fluids.

Furthermore, the operational flexibility of VCHPs (Figure 4(a)) can be increased by using a binary working fluid mixture comprising a refrigerant and an absorbent with a large boiling temperature difference (e.g. ammonia/water). The use of this working fluid mixture allows to reduce the high pressure in contrast to the pure working fluid (i.e. refrigerant) at the same temperature. However, as complete evaporation cannot be achieved, a solution circuit is required for the remaining liquid mixture, as depicted in Figure 4(b). Consequently, the evaporator and condenser in the VCHP (Figure 4(a)) are replaced by a desorber and an absorber, respectively, in the ACHP (Figure 4(b)). The key useful features of an ACHP compared to a VCHP are: (i) adaptability to the heat source and supply streams characteristics (temperature gliding), (ii) ability to operate at lower compressor pressure ratio, and (iii) reduced compressor discharge temperature.



(a) Single-stage VCHP without internal heat recuperator

(b) Single-stage VCHP with a solution circuit (referred to as ACHP).

Figure 4: Work-driven heat pump system configurations

There are a few manufacturers on the market that offer HTHPs using VCHP technology with supply temperatures above 90°C. Table 3 shows some of them and the main characteristics of their equipment. The highest temperature is 165°C. VCHP can be coupled with MVR to deliver heat at higher temperatures; for instance, Kobe Steel offers a unit producing superheated steam at 165°C using steam recompression (Kobelco SGH165, Table 3).

The ACHP technology based on ammonia/water mixture as working fluid is developed and commercialised by Hybrid Energy AS (also shown in Table 3). This ACHP supplies heat at temperatures above 110°C by upgrading heat from sources between 15°C and 65°C using standard refrigeration components operating below 25 bar.

Manufacturer	Product	Capacity (kW)	Max. Heat Supply Temperature (°C)	Working Fluid	Compressor Type
Vapour Compression Heat Pump (VCHP)					
Viking Heating Engines AS	Heat Booster HBS4	< 250	165	R1234ze, R1233zd, R1336mzzE, and R1336mzzZ	Piston
Kobe Steel	Kobelco SGH165	70–660	165 (using vapour recompression)	R134a/R245fa	Twin Screw
	Kobelco SGH120	70–370	120	R245fa	Two-stage Twin Screw
Ochsner	IWWHS ER3b	60–850	95	ÖKO(R245fa)	Screw
	IWWDSS R2R3b	170–750	130	R134a, ÖKO1	
	IWWDS ER3b			ÖKO(R245fa)	
Mayekawa	Eco Sirocco	65–90	120	R744 (CO_2)	Screw
Combitherm	HWW 245fa	62–252	120	R245fa	Piston
	HWW R1234ze	85–1301	95	R1234ze(E)	
Dürr thermea	thermeco$_2$	51–2200	110	R744 (CO_2)	Piston (up to 6 in parallel)
Friotherm	Unitop 22	600–3600	95	R1234ze(E)	Turbo (two-stage)
Absorption-Compression Heat Pump (ACHP)					
Hybrid Energy AS	GreenPAC	500–2000	100	ammonia/water	Piston[1]
	HyPAC-R	750–2000	120		
	HyPAC-S	1900–5000	120		

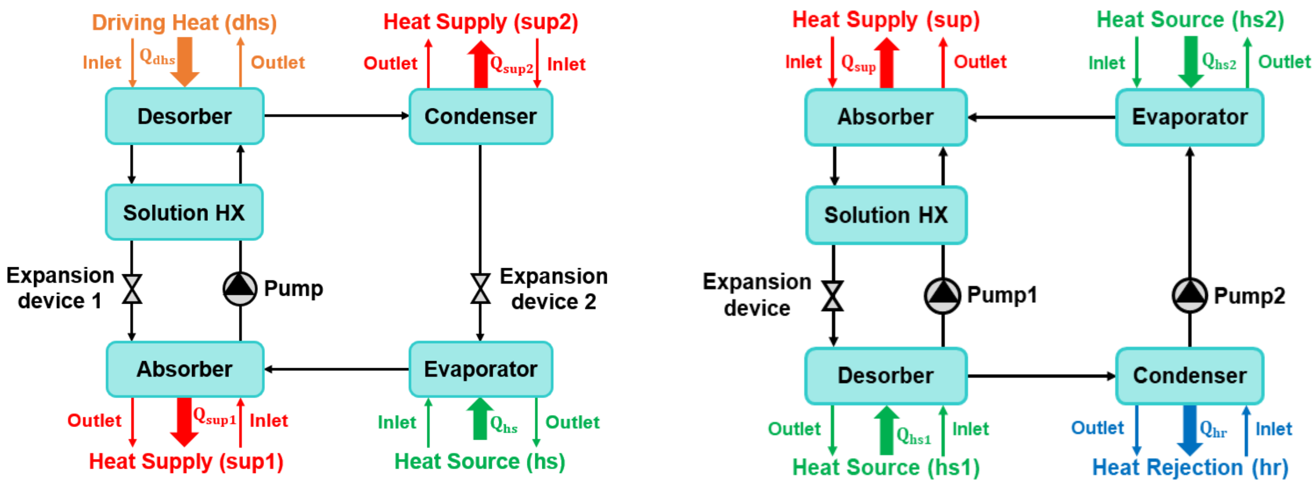
[1] *Arpagaus et al. (2018).*

Table 3: Commercially available work-driven industrial heat pumps with heat supply temperature above 90°C (Arpagaus et al., 2018; Hybrid Energy AS, 2016; EHPA, 2019; Viking Heat Engines AS, 2019)

HEAT-DRIVEN HEAT PUMPS

Heat-driven absorption heat pumps can be of two types: absorption heat pump (Type I, AHP) for heat amplification, and absorption heat transformer (Type II, AHT) for temperature amplification/boosting. The conventional working fluids used in this type of heat pump are lithium bromide (LiBr)/water and ammonia/water mixtures. Heat amplification in the AHP (from T_{hs} to T_{sup}, Figure 3) is achieved by using a high-quality energy input in the form of heat at high temperature (T_{dhs}). In the AHT, however, the portion of the heat from the heat source at intermediate temperature (T_{hs}, in Figure 3) is upgraded to a useful output heat supplied at high temperature (T_{sup}) while releasing the remaining heat at low temperature (T_{hr}) to a heat rejection medium (e.g. ambient air): $T_{sup}>T_{hs}>T_{hr}$. This temperature boosting by the AHT from T_{hs} to T_{sup} is achieved without any external high-quality energy input except for auxiliary electricity consumption. The single-stage LiBr/water AHP and AHT configurations are illustrated in Figure 5 (a, b), respectively.

LiBr/water AHP technologies are commercially available for heat supply temperature up to 100°C from well-known absorption chiller technology manufacturers. Some of these manufacturers are Broad Air-Conditioning, CNIM, Ebara, Johnson Controls-Hitachi, LG Electronics, Shuangliang Eco-energy, Thermax Ltd., and World Energy. These AHPs operate at a typical COP of 1.7 with a temperature lift of up to 50 K. Commercially available LiBr/water AHTs from these manufacturers supply heat at a maximum temperature of 175°C, and a COP between 0.4 and 0.5 with temperature lift of up to 50 K. The LiBr/water AHT from Thermax Ltd. has a heating capacity of 0.5 to 15 MW (Thermax Ltd, 2020). For high temperature lifts (> 50 K), advanced AHT cycle configurations with an increased number of stages (such as double-lift AHT) should be used (Lubis et al., 2017).



(a) Absorption heat pump (Type I heat pump) *(b) Absorption heat transformer (Type II heat pump)*

Figure 5: Single-stage LiBr/water absorption-based heat pumps

CHALLENGES AND FUTURE TRENDS

WORKING FLUIDS

The critical temperature and pressure values (T_c and P_c) and volumetric heat capacity of the working fluid are vital properties for the operation of VCHPs at high temperatures. Ensuring adequate lubrication and sealing of the compression chamber will be a challenge at high temperatures and oils with adequate viscosity and miscibility will have to be developed as well as good lubricant management, possibly including oil separation and cooling. Also, for future equipment, the global warming potential (GWP) and ozone depletion potential (ODP) of the fluids will have to be taken into consideration. Additionally, wet working fluids (anterograde) will tend to produce very high temperatures during the compression process, which could have an adverse effect on compressor reliability. Conversely, dry fluids (retrograde) require extra superheat at the evaporator to prevent wet compression, which can have a negative effect on COP A few fluids are available to work in a subcritical cycle with high heat supply temperatures (e.g. above 150°C), including R1233zd(E), R365mfc, R1336mzz(Z), pentane, acetone, and water. However, water has a low vapour pressure, and its compression is very difficult with commercially available compressor technologies. High pressure fluids can work in a transcritical cycle.

Absorption heat pumps (ACHP, AHP, and AHT) have the advantages of using natural working fluids, for example ammonia/water and LiBr/water mixtures.

However, these mixtures have disadvantages that limit the heat pump operating ranges, especially for high temperature applications (> 90°C). The use of ammonia/water mixture in the AHP and AHT for high temperature applications (> 90°C) is restricted due to the very high operational pressure. The use of LiBr/water mixture also limits the temperature lift due to LiBr crystallisation potential as the temperature drops or LiBr composition increases, while higher heat delivery temperatures are restricted due to corrosion and thermal instability of the working pair at high temperature (Ayou et al., 2019). The solubility of LiBr can be improved by using additives (e.g. inorganic salts, solvents, ionic liquids). Also, the choice of the working pairs can significantly influence the initial capital cost of the heat pump and dictate the required maintenance operations.

SYSTEM COMPONENTS

For work-driven heat pumps, the main challenge is to find a suitable compressor technology working at high temperature and compatible with the working fluid. The average and discharge temperatures in the compressor of high-temperature VCHPs are very high, so all technologies involving potential wearing need to find reliable lubrication warranting a sufficiently long-life operation, or to employ an oil-free compression technology. Furthermore, the electric motor faces difficult cooling in hermetic or semi-hermetic types given the high operating temperature at the evaporator. Several HTHP prototypes of have already been developed and successfully tested at high temperatures working with piston or screw compressors, and a few with scroll compressors. With current technology compressors, the tested HTHP prototypes have been able to reach delivery temperatures around 160 °C and temperature lifts of about 80 K (IEA, 2014). Although, the best compressor technology for high-temperature VCHPs, as well as for MVR systems, would be turbocompressors (Bantle et al., 2019). Their design has to be made specifically for the refrigerant fluid and the characteristic operating conditions, which makes their development cumbersome and expensive. As each industrial application is different, it will be difficult to find cost-effective solutions with this technology, except for applications with a large potential market and similar conditions.

Conclusion

- High-temperature heat pumps (HTHPs) are viewed as an attractive option to enhance energy efficiency and reduce the carbon footprint in many industries. Process industries, including agro-food, beverage, chemical, paper, and textile can significantly benefit from HTHPs

- The HTHP market is dominated by the vapour compression heat pump (VCHP) technology, but few heat pump products capable of supplying heat above 90°C are available; research and development activities are directed towards increasing the heat supply temperature. Research and development is focused on working fluids and compressor technology suitable for high-temperature applications.

- The current market shares of absorption-compression heat pump (ACHP) and absorption heat transformer (AHT) technologies are low, even though they have huge potential for high heat delivery temperature and large temperature lift.

- High-temperature industrial applications (> 100°C) using LiBr/water absorption heat pump (Type I heat pump) are restricted due to some drawbacks of the LiBr/water solution, including crystallisation, corrosion, and thermal instability at high temperatures.

- Applications of the ammonia/water absorption heat pump (Type I heat pump) are also limited to space heating and hot water production (< 80°C) because of very high operational pressure.

- For higher heat supply temperatures (> 100°C), commercially available heat pump technologies are the well-known and widely implemented VCHP, single-stage LiBr/water AHT and ammonia/water ACHP in addition to MVR open-loop heat pumps using steam as the working fluid.

- In conclusion, there is a a strong untapped potential for AHT and ACHP technologies to be integrated in process industries with high heat demand at temperatures above 160°C, which is the current temperature limit of VCHP technologies.

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IIR recommendations

The integration of high-temperature heat pumps (HTHPs) in process industries can reduce primary energy consumption for the industry, allowing fuel switching, and reducing CO_2 emissions related to energy consumption. HTHP is a key technology in the decarbonisation of process industries and, in order to exploit its full potential, the IIR stresses the need to:

- promote the economic and environmental benefits of HTHPs and raise awareness among relevant stakeholders, such as industries and governmental organisations;

- develop a roadmap relying on the different working groups of the IIR from the development of HTHPs – for large market penetration – to the deployment in industries;

- support research on promising HTHP technologies (vapour compression, absorption-compression and absorption heat transformer) to expand application areas and reduce costs;

- set up a platform for close collaboration between process industries, heat pump manufacturers and research institutes so as to accelerate the development of sustainable and cost-effective HTHP solutions and their implementation.

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