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Current status and new developments on high temperature heat pumps

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ABSTRACT

This review highlights the current status and new developments on high-temperature heat pumps with heat supply temperatures above 90°C. Besides the vapor compression heat pumps, the focus of this work is on absorption heat pumps, absorption heat transformers and compression-resorption heat pumps. Moreover, recent advancements in compressor technologies and working fluids for high-temperature vapor compression heat pumps are also highlighted. A few manufacturers are available in the high-temperature heat pump market segment that can supply single-stage water/LiBr absorption heat transformer and ammonia/water compression-resorption heat pump technologies. The heating capacity range of the commercial LiBr heat transformers is from 150 to 10,000 kW, while the thermal COP is between 0.45 and 0.50 at the temperature lift of up to 50 K. The commercially available compression-resorption technology delivers heat up to 120°C, while the obtained electrical COPs are about 6.1 (at 22 K lift), 4.3 (at 65 K lift) and 2.4 (at 75 K lift). Many theoretical and experimental studies have been carried out in order to extend the limit of achievable temperature lift and COP of high-temperature heat pumps.

Keywords: Heat Pump; High-Temperature, Absorption, Heat Transformer, Resorption, Compression, Industrial Applications.

1. INTRODUCTION

Industries need to reduce their carbon footprints in order to meet future carbon budgets set by international agreements such as the COP 21 (the 2015 Pairs climate conference). Thus, renewable and low carbon energy will replace fossil fuel options. Heat pumps will be one key technology for such sustainable energy transition. Nowadays heat pumps have gained increasing attention not only for residential but also for industrial applications. High-temperature heat pumps (HTHPs) offer an opportunity to upgrade low-to-medium temperature heat sources to high-temperature useful heat for industrial processes. The high-temperature heat (above 100°C) can be used in steam production, district heating or re-integrated into the industrial process thereby increases the efficiency of the system/process. HTHPs find their application in various sectors of industry (e.g., chemical, beverage, and paper). There have been lots of advancements in heat pump technology at lower heat delivery temperature (< 90°C), however, much lower progress has been made at high temperatures.

HTHPs are usually mentioned in connection with industrial applications where the need for heat sources at high temperatures (> 100°C) is frequent. In several research studies, one can find references to high temperature for heat pumps for any application above 60 - 70ºC, which is the usual limit for sanitary hot water production (to inhibit the growth of Legionella bacteria). District heating systems usually operate at higher temperatures, around 80ºC (3rd Generation), but heat pumps working in such sector must produce hot water in the range 80 to 90ºC. Cleaning and some process applications also operate at this level of temperatures, slightly below 100ºC. The heat pumps producing hot water at these temperatures are already available in the market. Only a few heat pump manufacturers supply heat pumps able to produce hot water at 90°C and above (Arpagaus et al., 2018). HTHPs are referred in this paper to those supplying heat at temperatures higher than 90°C.

To date, a limited number of reviews related to HTHP have been published and are briefly reviewed as follows. Arpagaus et al. (2018) and Bamigbetan et al. (2017) reviews were dedicated to vapor compression heat pumps, while Zhang et al. (2016) considered all types of heat pump systems and technologies with emphasis on industrial applications of heat pumps in China. Moreover, Xu and Wang (2017) reviewed the current status and future development of absorption heat pumps for the reuse of waste heat by emphasizing on three main aspects of the technology including absorption cycles, working pairs, and applications.

An excellent overview on the current state of the art and technology of HTHP can be found in a recent paper of Arpagaus et al. (2018), which contains a vast amount of detailed technical and scientific information about HTHPs. They were focused on the market status of HTHPs based on closed-cycle compression heat pump technologies, performance analysis of these cycles and their suitable refrigerants. The authors considered more than 20 HTHPs from 13 manufacturers, which have been identified on the market that are able to provide the heat supply temperature of at least 90°C and maximum of 165°C. The food, paper, metal, and chemical industries are potential application areas of the HTHP technologies with heating capacity in the range of 20 kW and 20 MW, while their electrical COP values vary between 2.4 and 5.8. These heat pumps are typically based on single-stage vapor compression cycle architecture and with their modifications (inclusion of internal heat exchanger, subcooler, economizer and flash tank(for steam generation)). Also, they differ mainly in the type of compressor and refrigerant employed in the system. The main type of compressor used in such systems are twin-screw, piston, screw, and two-stage turbo machine while the refrigerants used are R245fa, R717, R744, R134a or R1234ze(E). Moreover, the refrigerants R1336mzz(Z), R718, R245fa, R1234ze(Z), R600, and R6001 were examined in detail and R1336mzz(Z) enables to achieve exceptionally high heat supply (sink) temperatures of up to 160°C.

Bamigbetan et al. (2017) review work was focused on the use of natural refrigerants (e.g., ammonia, carbon dioxide, water, butane, propane) for HTHPs. Their review has shown the different challenges for the implementation of these HTHPs such as fluid selection, component development to system optimization to mention a few, while, discussing the possible innovative solutions to address these challenges. The HTHPs with natural refrigerants have shown to be a potential environmental friendly solution with the capabilities of energy efficiency increase in industrial processes. The research advances and development in the application of industrial heat pumps in China with the emphasis on three industrial fields (drying of wastewater sludge, crude oil heating in oil field, and process heating in printing and dying) were carried out by Zhang et al. (2016). The review addresses research progresses on refrigerants and different type of systems (i.e., multi-stage, double-effect, compression-absorption, solar assisted and commercial heat pump systems). Chua et al. (2010) have reviewed heat pump systems, focusing on performance enhancement methods (e.g., multi-stage cycles), hybrid heat pump systems, and their applications in selected industries. Whereas, Arpagaus et al. (2016) were focused on the multi-temperature applications of mechanically-driven heat pumps and refrigerators. The present review article is envisioned to complete and address recent advancements on HTHP technologies that have aimed to supply heat at a temperature above 90°C. In this review, absorption heat pumps, compression-resorption heat pumps and vapor compression heat pumps for high-temperature applications are discussed with emphasis on new developments.

2. HIGH-TEMPERATURE HEAT PUMP SYSTEMS AND TECHNOLOGIES

HTHP technologies are classified into three main types; namely, vapor compression heat pump, absorption heat pump and the combination of compression and absorption technologies. In this section and subsequent sections, we focused on these technologies at high-temperature applications.

2.1. Vapor compression based heat pumping

HTHP technology based on mechanical vapor compression process is the most exhaustively studied heat pumping option, and the reader is referred to Arpagaus et al. (2018, 2016). From the thirteen manufacturers mentioned above, only two (Kobe Steel and Viking Heat Engines SA) offer HTHPs with maximum heat supply temperature above 130°C (Arpagaus et al., 2018). The rest of the manufactures offer HTHPs with maximum heat supply temperatures between 90 and 130°C, and of which five of them only offer at 90°C. The company Kobe Steel offers an HTHP (Kobelco SGH 120) with a nominal capacity of 380 kW producing saturated steam at 120°C, from a water heat source stream from 25 to 65°C with a Coefficient of Perforformance (COP) of 3.2 at 65°C heat source temperature. This unit incorporates an especially designed two-stage screw compressor and uses R245fa as a refrigerant. Furthermore, Kobe Steel also offers a heat pump unit (Kobelco SGH165) producing steam at 165°C by using a vapor recompression process. Viking Heat Engines SA offers a heat pump (HeatBooster HBS4) able to produce hot water at temperature up to 160°C with heating capacity up to 200 kW (Viking Heat Engines, 2018). It employs an especially designed piston compressor (designed together with AVL – an engine designing company) using R245fa or R1336mzz-Z refrigerants.

2.2. Absorption based heat pumping

Absorption heat pumps (Type I Heat Pumps, AHPs) and absorption heat transformers (Type II Heat Pumps, AHTs) can be used to upgrade industrial waste/excess heat to useful temperature levels. Since the heat pumping in AHTs is a temperature increasing process, the AHTs are referred as temperature boosters. Whereas in the case of AHPs the heat pumping process is heat increasing process, hence the AHPs are referred as heat amplifiers. The AHPs require high-temperature driving-heat source (T_{dhs}) in order to upgrade the heat source at low-temperature (T_{hs}) to an intermediate useful temperature level (T_{supply}). AHTs upgrade a portion of the heat from the heat source (T_{hs}) to a higher temperature level (T_{supply}), while rejecting the rest of the heat at low temperature (T_{amb}) to the heat sink (e.g., ambient).

The most commonly employed working pairs, refrigerant/absorbent pairs, in the AHPs and AHTs are ammonia/water and water/LiBr mixtures. The single-effect AHP and AHT are the simplest/basic configurations for AHP and AHT technologies. However, the single-effect AHP and AHT are limited in the temperature lift (defined as $\Delta T_{lift} = T_{supply} - T_{hs}$). The COP of a single-effect AHP is also limited regardless of the driving-heat source temperature level. Hence, there are two ways to improve the performance of AHPs and AHTs: either to increase the efficiency of the heat pump (i.e., higher COP) or enlarge the temperature lift while maintaining the COP or with a small reduction on the COP. The multi-effect and GAX (generator-absorber heat exchange) concepts are used to enhance the energy efficiency, while the double-lift concept is used to increase the temperature lifts of AHPs and AHTs (Alefeld and Radermacher, 1994). Therefore, for instance, the double-effect AHP (DEAHP) is more energy efficient than the single-effect AHP, however, it is more appropriate for conditions where the heat source is at a high-temperature and small temperature lift is needed (Zhang et al. 2016).

2.2.1. Absorption Heat Pump

The cycle configurations of AHPs are the same as those of absorption refrigeration cycles, except that the desired outputs are different – heating in the case of the heat pump cycle while refrigeration effect for refrigeration cycles. The single-effect AHP consists of seven main components an absorber, condenser, evaporator, desorber, solution heat exchanger, solution circulation pump and expansion device. The single-effect ammonia/water AHP is not suitable for industrial heat pumping applications above 90°C with market available standard components, but it is usually used for residential heating and hot water production below 80°C. It is due to the high operating pressures at these heat supply temperatures, e.g., at temperatures higher than 95°C the corresponding pressure is above 53 bar for ammonia composition of 96% (in mass). The single-effect water/LiBr AHP is also limited in application range due to the working pair water/LiBr adverse characteristics such as crystallization, corrosion, and instability at high temperature. Hence, the heat supply temperature levels in single-effect AHP may reach approximately 100°C (Zhang et al., 2016).

The single-effect water/LiBr AHPs developed by LG Electronics (2018) are designed to supply heating up to 55 - 90°C with a heating capacity higher than 300 kW (349 to 30,218 kW). The French manufacturer CNIM provides single-effect water/LiBr AHPs with heat supply temperature 60 to 80°C at a COP of about 1.7 (CNIM, 2019). The heat source temperature is between 25 and 35°C. Hot

water, steam, gas, and hot oil can be used as a driving heat source in the range of 90 to 500°C. Two DEAHPs with a heating capacity of 150 kW has been installed at the experimental test facility of Plataforma Solar de Almería (Spain) (Alarcón-Padilla et al., 2010). This DEAHP is operated to supply hot water at about 65°C to the multi-effect desalination unit using driving steam at 150°C.
A two-stage water/LiBr absorption machine was developed by the company ENTROPIE (now CNIM). The machine can operate in two modes as a chiller and as a heat pump. When it works as double-effect chiller it is driven by heat at 170°C using natural gas boiler (at high-pressure desorber) and can take also heat at low-pressure desorber (e.g., using heat from solar thermal collectors). The machine can also work as a double-lift heat pump delivering heat at 70 - 100°C using driving hot water at 160°C with a COP of 1.3 (Figueredo, 2012).

2.2.2. Absorption Heat Transformer

The single-stage water/LiBr AHT is the most commonly investigated configuration in the literature. The technical challenges (e.g., corrosion at high temperature) associated with this system are similar to the challenges experienced in the design of double-effect water/LiBr chillers, which are dressed effectively in the manufacturing of such technology (Herold et al., 2016). The single-stage water/LiBr AHT can increase about 50% of the waste heat energy by up to 50°C (typically in the range of 30 - 40°C (Parham et al., 2014)). Hence, such systems are ideally suited to applications in which only a relatively small temperature increases are needed.

The single-stage water/LiBr AHTs from LG Electronics (2018) is designed to supply heat up to 120°C, with a heating capacity higher than 300 kW. It utilizes hot water at 70°C as a driving heat source. However, in order to obtain greater temperature lifts (above 50 K), advanced AHT cycles must be used. Using advanced AHTs with an increased number of stages decreases the quantity of energy which may be upgraded (i.e., reduced COP); but it enables higher temperature lifts to be attained. In the literature, two types of two-stage AHT cycles are often considered, which are referred as: double (lift) absorption heat transformer (DAHT) and double-stage absorption heat transformer (DSAHT) (Donnellan et al., 2015). The DAHT uses the concentrated solution coming from the desorber as the absorbent in the absorber-evaporator unit. Hence, the DSAHT has more components and needs more investment in equipment, whereas DAHT is considerably simpler than the DSAHT. Besides, for much higher temperature lifts, the triple-stage water/LiBr AHTs may be used to attain temperature lifts of up to 145 K by upgrading about 20% of the available waste heat.

2.3. Resorption based heat pumping

The resorption concept is according to two basic principles. First, the working pair is a zeotropic mixture with large boiling temperature difference (e.g., ammonia/water). Second, the condensation and evaporation processes (in the reverse Rankine cycle) are replaced by absorption (in a resorber) and desorption (in a desorber) processes, respectively. Since the evaporation of the working pair is not complete, the remaining liquid from the desorber is pumped to the resorber, which forms a solution circuit between the desorber and resorber referred as resorption circuit. There are different possibilities to combine the resorption circuit with mechanical vapour compression and solution circuit of both AHP and AHT. Therefore, the combined/hybrid heat pump types are realized, which are compression-resorption heat pump (CRHP), absorption-resorption heat pump (ARHP) and resorption-absorption heat transformer (RAHT).

The advantages of CRHP, ARHP and RAHT cycles over the individual cycles (i.e., absorption cycle and compression cycle) are, first, the reduction of high vapor pressure relative to the pure refrigerant (in the working pair). Second, the temperature glides of the absorption and desorption processes compared to isothermal condensation and evaporation processes of pure refrigerants. These infer that *(i)* – these heat pumps approach the reversible cycle (e.g., Lorenz cycle) with variable temperatures - which can result in an increased COP due to reduction of entropy generation in the non-isothermal heat addition and rejection processes, *(ii)* – they can achieve higher supply temperatures than the individual cycles at the same operating pressure, and *(iii)* – it has additional degrees of freedom for operational flexibility. Hence, the CRHPs, ARHPs, and RAHTs are appropriate technologies for high-temperature industrial process heat supply and waste/excess heat recovery as these processes often require large sink-source temperature glides.

As the CRHP is a combination of two different types of technologies, i.e., absorption and vapor compression so that the CRHP benefits from both technologies' best features. The CRHP cycle combines the advantages of the compression cycle (higher performance, i.e., higher COP) and absorption heat pump (high-temperature lifts and temperature gliding). The cycle is also known as vapor compression cycle with solution circuit (Groll, 1997); moreover, it is also referred as hybrid absorption-compression cycle in the literature (Jensen, 2016). The single-stage CRHP using an ammonia/water mixture is a promising technology for high-temperature applications using existing standard commercial components (Jensen, 2016).

In addition to single-stage CRHP cycle, there are several possibilities to combine the vapor compression (either with single or multi-stage compression processes) with advanced absorption heat pump technologies in order to improve the performance or extend operating ranges. For instance, two-stage compression with internal heat recovery CRHP (Jensen, 2016; Wersland et al., 2018) and CRHP with absorber-desorber heat exchange (Groll, 1997) have been investigated in the literature. Wersland et al. (2018) studied the performance of ammonia/water CRHP using two types of compressors: a single-stage screw compressor and two-stage piston compressor. The study was carried out at a heat source temperature of 30°C to obtain a heat at 115°C from 95°C. It was obtained a COP of 1.37 and 2.04 for screw compressor and two-stage piston compressor, respectively. Kabelac et al. (2018) investigated the performance of single-stage ammonia/water CRHP with open screw compressor using the experimental test rig built at the Institute for Thermodynamics in Leibniz Universität Hannover (Germany). They obtained a maximum of 2.5 electrical COP at the highest temperature lift of 43 K when the heat source at 59°C, and it delivers a heating output of 40 kW.

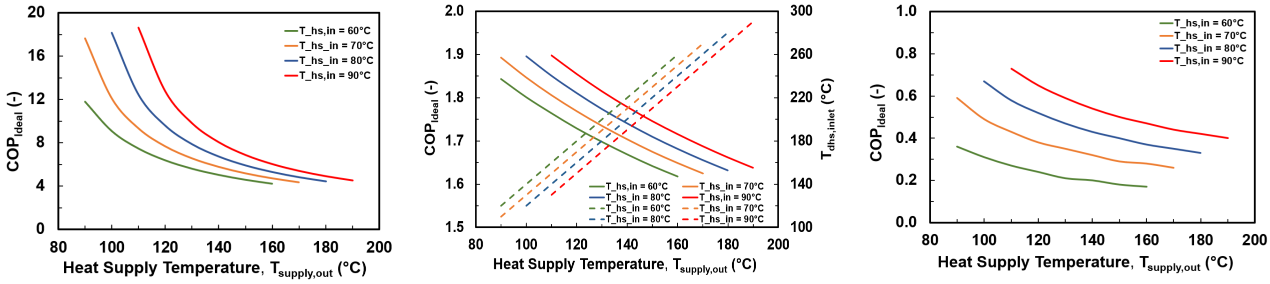
3. PERFORMANCE COMPARISON OF DIFFERENT HEAT PUMP CYCLES

For heat pumps operating at two temperature levels, such as VCHP with pure working fluids, their theoretical maximum COP (COP_{ideal}) is described by Carnot COP. The ideal COP of VCHP and CRHP are dependent only on these two temperature levels, which are represented by average entropic temperatures for heat transfer processes occurring at variable temperatures. Then, the ideal COP is defined as $COP_{ideal} = \hat{T}_{supply}/(\hat{T}_{supply} - \hat{T}_{hs})$ where $\hat{T}_{supply}$ and $\hat{T}_{hs}$ are average entropic temperatures for heat supply and heat source, respectively, at variable temperatures. However, the actual COP of the heat pump is lower than the ideal COP due to inherent internal and external irreversibilities. Hence, the second law efficiency of the heat pump ($\eta_{II,HP}$, defined as $\eta_{II,HP} = COP/COP_{ideal}$) can be used to evaluate the performance of the heat pump technology with respect to the theoretical maximum performance. It relates the COP to maximum achievable COP for finite heat reservoirs in terms of a Lorenz cycle and therefore, it gives an indication about the potential improvement possibilities. In Fig. 1 (a), the ideal COP of VCHP and CRHP cycles are shown for a temperature lift from 20 to 100 K at a heat source inlet temperature ($T_{hs,in}$) of 60, 70, 80 and 90°C.

The AHP and AHT are operating at least at three temperature levels. Hence, the ideal COP of AHP and AHT are dependent on the three temperature levels: $\hat{T}_{dhs} > \hat{T}_{supply} > \hat{T}_{hs}$ for AHP (Type I heat pump) and $\hat{T}_{supply} > \hat{T}_{hs} > \hat{T}_{cw}$ for AHT. The ideal COP of AHP and AHT are given in Eq. (1).

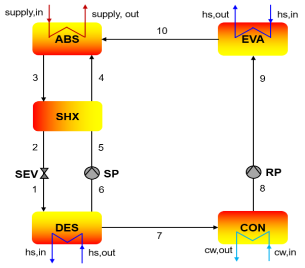
$$COP_{ideal,AHP} = \frac{\hat{T}_{dhs} - \hat{T}_{hs}}{\hat{T}_{dhs}} \cdot \frac{\hat{T}_{supply}}{\hat{T}_{supply} - \hat{T}_{hs}} \qquad COP_{ideal,AHT} = \frac{\hat{T}_{hs} - \hat{T}_{cw}}{\hat{T}_{hs}} \cdot \frac{\hat{T}_{\square upply}}{\hat{T}_{supply} - \hat{T}_{cw}} \qquad \text{Eq. (1)}$$

The ideal COPs of AHT and AHP with the driving-heat source inlet temperatures are presented in Fig. 1 (a) at different values of $T_{hs,in}$. The temperature glides in the driving-heat source, heat supply and, heat source streams were assumed as 20 K. The heat rejection stream (i.e., cooling water) inlet/outlet temperatures of the AHT was set at 30/40°C. Furthermore, the thermodynamic performance of the different types of heat pump cycles was reported at high-temperature heat supply conditions (> 90°C) and heat source temperatures. The selected heat pump cycles are single-stage water/LiBr AHT (SSAHT), double-lift AHT with water/LiBr (DAHT), ammonia/$LiNO_3$ resorption absorption heat transformer (RAHT) and ammonia/water single-stage CRHP cycle. These cycles are relatively less complex than other advanced absorption cycle configurations (e.g., multi-stage multi-effect cycles, GAX cycles) and some of them are implemented practically. The performance and schematics of these heat pump cycles are presented in Fig. 1 (b – e).

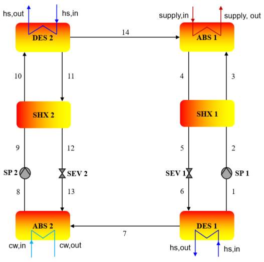


Ideal VCHP/CRHP cycle Ideal AHP cycle Ideal AHT cycle

a) Ideal maximum COP of different types of heat pump cycles with heat transfers at variable temperatures.

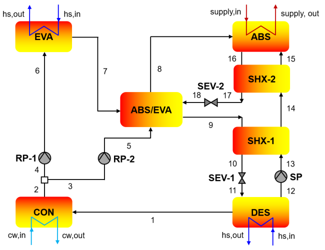


T_{supply} (°C)	130
T_{hs} (°C)	80
T_{cw} (°C)	25
ΔT_{lift} (K)	50
COP^1 (-)	0.480
$\eta_{II,HP}$ (%)	80.3

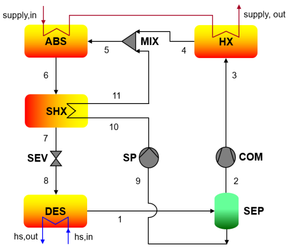


T_{supply} (°C)	120
T_{hs} (°C)	90
T_{cw} (°C)	30
ΔT_{lift} (K)	30
COP^1 (-)	0.401
$\eta_{II,HP}$ (%)	55.6

b) Single-stage water/LiBr AHT (SSAHT) **c)** Single-stage ammonia/LiNO$_3$ RAHT



T_{supply} (°C)	160
T_{hs} (°C)	70
T_{cw} (°C)	25
ΔT_{lift} (K)	90
COP^1 (-)	0.313
$\eta_{II,HP}$ (%)	74.4



T_{supply} (°C)	100
T_{hs} (°C)	35
T_{cw} (°C)	N/A
ΔT_{lift} (K)	65
COP^2 (-)	4.3
$\eta_{II,HP}$ (%)	51.3

d) Double AHT with water/LiBr (DAHT) **e)** Single-stage ammonia/water CRHP

Figure 1. Performance comparison of ideal heat pump cycles, SSAHT, DAHT, RAHT and CRHP.

Note: ^{1} – thermal COP; ^{2} – electrical COP; $\eta_{II,HP}$ – second law efficiency of heat pump; N/A – Not applicable.

4. GLOBAL DEPLOYMENT OF INDUSTRIAL HTHP TECHNOLOGIES

The potential of AHT and CRHP technologies to upgrade industrial waste heat (and excess heat) to a useful temperature level (> 90°C) have been implemented in several industrial applications. In Table 1, some of these HTHP industrial deployments are presented. However, limited high-temperature industrial applications are available for AHPs. For instance, the single-effect water/LiBr AHP with a heating capacity of 7.5 MW is installed at the Schweighofer Fibre GmbH (Austria) (IEA, 2014a). It is used to recover waste heat (below 50°C) from the flue gas of the biogas plant and delivered the heat at 95°C. Steam at 165°C from the biomass plant is utilized to drive the AHP. The average COP about 1.6 was achieved for a total operation hour of 37,000 h per annum.

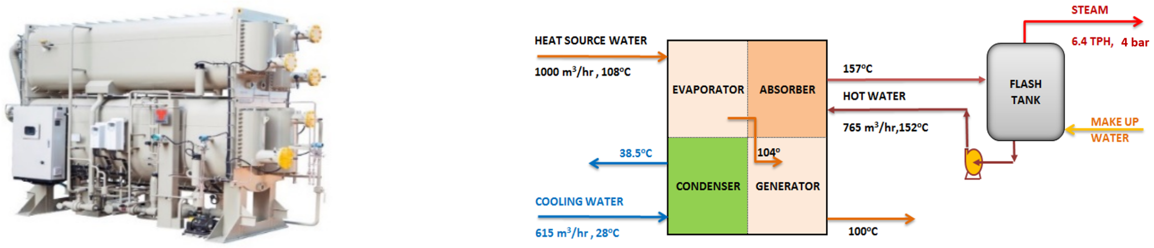
Thermax Ltd (2018) has developed single-stage water/LiBr AHT with heating capacities between 500 and 10,000 kW. They can supply heat at a maximum temperature of 160°C, typically with a temperature lift of 50 K. The COPs are in the range of 0.45 to 0.5. Steam condensate (e.g. from steam turbine), hot water, process condensate between 80 and 150°C are used as a heat source, which either supplied individually or in combination. Thermax single-stage water/LiBr AHT type (shown in Fig. 2(a)) has been used in a poly film manufacturing plant for PV cells. The part of the heat rejected in the cooling process was utilized, by using the single-stage water/LiBr AHT, to generate steam at 4 bar which finds use within the plant. The schematic of the heat recovery process is depicted in Fig. 2(b). Moreover, Thermax single-stage water/LiBr AHTs have been implemented in food industries in Italy and Germany (Table 1). The AHTs are used to produce hot water at 135°C for drying process of pasta making in the Baronia Pasta Factory (Italy) while hot water produced at 105°C is utilized for vegetable cooling in the pre-cooked meal production process in Renken (Germany). In both cases, hot water at 93°C and 90°C, respectively, from engine jacket water are used as a heat source.

Table 1: Worldwide deployment of absorption heat transformer (AHT) and compression-resorption heat pump (CRHP) technologies for high-temperature (> 90°C) industrial applications.

Company Name (Country)	Manufacturer	Cycle Type	Working Pair	Temperature, T (°C)			Heating Capacity (kW)	COP (-)
				$T_{hs,in/out}$	$T_{cw,in/out}$	$T_{SINK,in/out}$ (ΔT_{lift})		
Asia Silicon Co. Ltd (China)	Thermax Ltd	Single-stage AHT	H_2O/LiBr	108/100	28/38.5	152/157 (49)	~4189	0.47^1
Baronia Pasta (Italy)	Thermax Ltd	Single-stage AHT	H_2O/LiBr	93/75	N/R	125/135 (60)	~1202	0.46^1
Renken Germany (Germany)	Thermax Ltd	Single-stage AHT	H2O/LiBr	90/80	N/R	95/105 (15)	~449	0.47^1
Borregaard ASA (Norway)	Hybrid Energy AS	Single-stage CRHP	NH_3/H_2O	73/46	N/A	70/95 (22)	2000	6.1^2
Frevar (Norway)	Hybrid Energy AS	Two-stage CRHP	NH_3/H_2O	20/14	N/A	75/95 (75)	800	2.4^2
Løgumkloster District Heating plant (Denmark)	Hybrid Energy AS	CRHP	NH_3/H_2O	35/17	N/A	35/100 (65)	1300	4.3^2
Alcohol Industry (Japan)	Johnson Controls HITACHI	Single-stage AHT	H2O/LiBr	N/R	N/R	107/112 (N/R)	2,475	N/R
Not Provided (N/R)	Johnson Controls HITACHI	Single-stage AHT	H_2O/LiBr	90/85	N/R	135/140 (50)	300	0.45^1
Machinery (N/R)	Johnson Controls HITACHI	Single-stage AHT	H_2O/LiBr	90/85	27/31	133/137 (47)	150	N/R

Note: ^{1} – Thermal COP; ^{2} – Electrical COP; cw – Cooling water; hs – Heat source; ΔT_{lift} – Temperature difference between heat sink outlet and heat source inlet (Jensen, 2016); N/A – Not applicable; N/R – Not reported.

Johnson Controls–Hitachi Air Conditioning Solutions offers single-stage water/LiBr AHT with a heating capacity from 150 to 2,475 kW and supply temperature of 70 to 140°C. The AHT uses waste heat, below 100°C, of jacket water of cooled engines, waste heat from industrial processes and distillation units, while rejecting heat at low temperature, e.g. 30°C, to cooling water, underground water or recovery cooling water. A typical example of a single-stage water/LiBr AHT of this manufacturer is used to recover heat of 90°C from hot water of co-generation system to produce steam at 2 bar or deliver hot water at 140°C with heating capacity of 300 kW and COP of 0.45. At the synthetic rubber plant of the Yanshan Petrochemical Corporation (China), an industrial-scale 5 MW single-stage water/LiBr AHT was installed and later expanded to include two other sets of similar AHT with heating capacity of 7 MW (Ma et al., 2003; Zhang et al., 2016). The heat supplied by the AHTs were used to heat hot water for 95 to 110°C, with an average COP of 0.47 and maximum temperature lift of 25 K. The AHTs are used to recover waste heat from steam and organic vapor mixture at 98°C.



(a) **(b)**

Figure 2. Single-stage water/LiBr absorption heat transformer installed in poly film manufacturing plant in China (Thermax Global, 2018). Courtesy of Thermax.

The CRHP working with ammonia/water mixture is developed by Hybrid Energy AS (2018). The technology is commercialized by the company for high-temperature industrial heat pumping applications, with the first commissioning in 2004. It provides heat at temperatures above 110°C by recovering waste/excess heat between 15°C and 65°C using standard refrigeration components (operating below 25 bar). The single-stage CRHP from the Hybrid Energy AS is designed for pre-heating of feed water in Bio-refinery process plant in Borregaard (Norway) and commissioned in 2017. The system has reduced the plant's energy consumption approximately by 60 GWh/year. In 2016, the wastewater and sewage treatment plant of Frevar, in Fredrikstad (Norway), used a two-stage ammonia/water CRHP to recover heat from biogas upgrading plant and treated wastewater. The heat delivered to the central heating system of the plant and, then the hot water (at 95°C) is utilized for industrial processes including preheating of sludge and heating buildings. Løgumkloster district heating plant in Denmark installed the CRHP from Hybrid Energy AS in 2015. The CRHP recovers heat at low temperature (35°C) from concentrated solar power facility and supplies the upgraded heat (from 35 to 100°C) to the district heating network. This heat pump simultaneously provides chilled water at 17°C to processes need cooling in the solar facility.

5. CHALLENGES AND OPPORTUNITIES FOR FUTURE INDUSTRIAL APPLICATIONS

5.1. High-temperature heat pumping challenges

5.1.1. Working fluids

Many pure working fluids have been considered for HTHPs based on vapor compression cycles (Arpagaus et al., 2018). As in other heat pumps (e.g., heat pumps for residential applications), the most important characteristics of the fluids to be considered are the critical temperature and pressure and its volumetric heat capacity at the heat source temperature. Additionally, dry fluids (Retrograde) will need an extra superheat at the evaporator, whereas wet fluids (Anterograde) will tend to produce very high discharge temperatures which could negatively affect the reliability of the compressor. The global warming potential (GWP) and ozone depletion potential (ODP) of the fluids are also important characteristics to be considered for future equipment.

Fig. 3 shows the critical temperature of most employed working fluids with an indication of the kind of fluid they are. The bars, in Fig. 3, connect the NBP (normal boiling point) with the critical temperature of each fluid. One line has been drawn at 150°C just as a reference. As it can be observed in Fig. 3, only a few fluids would be available to work in a subcritical cycle with sink temperatures about 150°C, i.e., R1233zd(E), R365mfc, R1336mzz(Z), pentane, acetone and of course water. Water is maybe an adequate fluid for very high-temperature heat pumping applications, but for the analysed range it still has very low vapor pressure and its compression is very difficult with commercially available compressor technologies. R365mfc is an HFC and has a relatively high GWP (804) and it is an A2 fluid. R1233zd (E) is an HCFO while R1336mzz (Z) is an HFO, both with a very low GWP and with almost null ODP, and they are A1 fluid. Pentane is an HC and so an A3 fluid. High-pressure fluids could work in a transcritical cycle. This would have the advantage of the high glide of the temperature of the fluid along the gas-cooler to match the increase of temperature of the secondary fluid on the sink side. Also, however, sub-critical cycles can exploit this glide by producing a high subcooling.

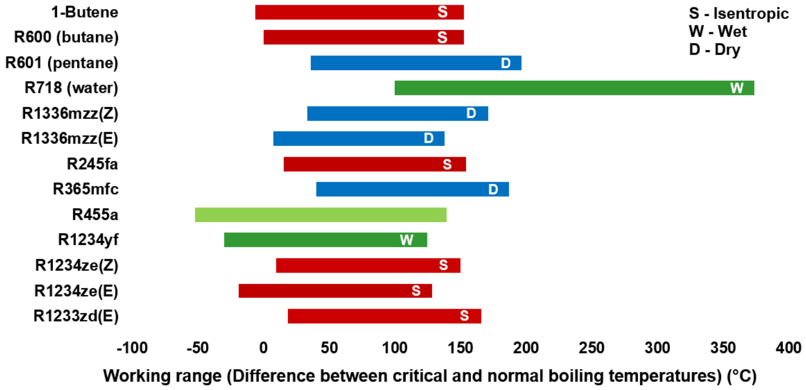


Figure 3. Working range of mostly used working fluids: dry, wet and isentropic working fluids.

One of the main advantages of AHP, AHT, and CRHP technologies is the use of natural working pairs (e.g., ammonia/water, ammonia/$LiNO_3$, water/LiBr. However, these mixtures have their own drawbacks. The use of ammonia/water mixture in AHP and AHT for high-temperature applications (> 90°C) has an effect of operating at high pressure. The use of water/LiBr limits the temperature lift because of the crystallization potential of LiBr when the temperature drops or LiBr composition increases, while higher heat supply temperatures are restricted due to corrosion and instability of the working pair at high temperature. The solubility of LiBr can be enhanced using additives (e.g., inorganic salts, solvents, ionic liquids). However, it may have an adverse effect on other properties of the mixture such as viscosity, vapor pressure, corrosiveness, etc. Besides its effect on the application ranges, the working pairs can significantly influence the initial capital cost of the unit and dictate required maintenance operations. Therefore, the selection of the working pair is a crucial aspect to be considered for the selection of AHPs and AHTs.

5.1.2. System components

The main challenge of HTHPs based on VCHP and CRHP cycles is the compressor technology. The average and discharge temperatures in this type of HTHP are very high, so all technologies involving potential wearing need to find reliable lubrication warranting a sufficiently long life. Compressors requiring no lubrication would be in principle the most adequate technology. Apart from the lubrication, the electric motor must be also quite special since the high operating temperatures at the evaporator lead to high mass flow rates and high torques. Therefore, the motor required for this application is much larger than the one corresponding to a similar displacement compressor for standard applications. Additionally, the cooling of the motor and the oil is difficult to do with high suction temperatures in hermetic or semi-hermetic compressors. Therefore, the best compressor technology for HTHPs would be turbocompressors. However, the design of these compressors must be specifically done depending on the refrigerant fluid and the operating conditions. Their development is cumbersome and very costly. As each industrial application is different, it is difficult to find cost-effective solutions with this technology except for applications with a large potential market and similar conditions.

Most of the HTHP prototypes that have been tested at high temperatures are working with piston compressors and a few with screw compressors. Électricité de France (EDF) presented an experimental study about an HTHP using a scroll compressor and a new fluid named as ECO3 (IEA, 2014b). This heat pump was able to reach 138°C of condensation temperature with an evaporation temperature of 60°C. The Austrian Institute of Technology (AIT) also reached high temperatures with a 12 kW semihermetic piston compressor working with refrigerant R1336mzz-Z (IEA, 2014b). The condensation temperature is 125°C with a temperature lift of 70 K. Recently, the Norwegian University of Science and Technology (NTNU) and SINTEF investigated an HTHP with semihermetic piston compressor using butene as a refrigerant. The condensation and evaporation temperatures are 115°C and 50°C, respectively, while the compressor discharge temperature is 140°C. Therefore, the maximum attained condensation temperature using volumetric compressors seems to be 125 – 135°C for the moment. The actual efficiency of the compressors at these extreme conditions is relatively low and the reported values of the COP are below 3.0, with about 70 K temperature lift and the highest condensation temperatures. Comparing these COP values with the 50% of ideal (reversible) COP values (i.e., estimated as attainable values) shown in Fig. 1 (a), there is still a significant high margin for improvement. A double-lift water/LiBr AHT was developed and experimentally tested to demonstrate its applicability for steam generation at 8 bar with a lift of about 90 K. This DAHT development was carried out under the research project “Next Generation Heat Pump Technology” supported by NEDO (New Energy and Industrial Technology Development Organization), Ebara Refrigeration Equipment & System Co.Ltd and Waseda University in Japan (Lubis et al., 2017). The authors demonstrated that the technical challenges related to corrosion and crystallization, particularly at high-temperature absorber, was handled well. Thereby, the DAHT system operates steadily and efficiently (at a COP of exceeds 0.3 for a heat source temperature of 84°C). Furthermore, a surfactant additive (2-Ethylhexanol) was used to enhance heat transfer rates. In addition, the European project Indus3Es (2016 – 2020) is developing an AHT for upgrading industrial surplus heat available at low temperature to a useful level below 130°C, depending on the ambient temperature. In this project, two 10 kW lab-scale prototypes and five 50 kW capacity have been tested with the final aim of designing a machine that revalorizes about 200 kW of waste heat from 95 to 135ºC.

5.2. Future opportunities and outlooks

Despite the challenges mentioned above, the opportunities for primary energy savings and reduction of greenhouse gas emissions will continue to build high interest in HTHP applications. Furthermore, there is a necessity to move to low carbon energy solutions and the use of natural refrigerants. It is due to fossil fuel supply depletion, the fuel penalty imposed by governments, and the banning of refrigerants with high GWP and ODP by international agreements. The use of HTHPs as stepping stones towards the replacement of boilers and steam systems, which generates potentially much greater savings where the existing systems have low efficiency. As conventional energy costs are increasing because of imposed legislation by governments, industrial payback period values are easily attainable. Therefore, the need for research and development of HTHP's potential for energy conservation and reduction of CO_2 emissions is enormous.

In the VCHP technology, the main focuses on the R&D fronts are on the working fluids employed in the system and compressor technologies for high-temperature applications. Corberán et al. (2019) studied the performance of an HTHP based on vapor compression cycles for industrial applications, which needs pressurized hot water (> 100°C) and saturated steam or for high-temperature thermal storage applications. They analysed the performance of the HTHP using dry (R1336mzz(Z), R365mfc), wet (water, acetone) and isentropic (R1233zd(E), R245fa, butene) refrigerants. According to their simulation results, the isentropic refrigerants have the highest performance compared to dry and wet refrigerants. From these candidate refrigerants, R1233zd(E) is the most suitable refrigerant regarding safety and performance. However, it reaches a maximum temperature lift of 73 K and acetone seems to be a good candidate for high-temperature lifts. There are two possible R&D directions in order to address the downsides of the conventional working pairs used in the AHP and AHT technologies. They are *(i)* - altering undesirable characteristics of the working pairs and *(ii)* – to identify new working pairs so that to replace the conventional working pairs. Consequently, the temperature lift and the heat supply temperature of the water/LiBr AHT and AHP could be enlarged using additives (e.g., other inorganic salts, solvents, ionic liquids) to increase the solubility of LiBr and reduce corrosion. Another approach is to select other absorbents (e.g., ionic liquids, organic fluids) for natural refrigerants such as ammonia, water, and carbon dioxide.

The CRHPs using wet compression has been considered in the literature due to its promising advantages (Gudjonsdottir et al., 2018). The benefits of wet compression include reduction of consumed power compared to VCHPs and avoid vapor superheating, which is particularly attractive for high-temperature applications. And, the solution pump is not needed. The COP of CRHP with ammonia/water mixture can be increased by above 15% due to the use of wet compression.

As highlighted in the literature, the use of AHTs has several advantages from a thermodynamic viewpoint. However, the economic feasibility of AHTs has not been yet sufficiently reported. Regardless of the amount of heat upgraded by the AHT, unless the AHTs can generate adequate returns on investment so that acceptable short payback periods are obtained, they are unlikely targets for investment. This is mainly due to the system CAPX (capital expenditure). Therefore, more efficient component types should be pursued which can reduce the capital costs of AHTs. Moreover, the price of utilities for example electricity is also extremely influential for economic viability.

The subject of HTHPs has attracted the interest of researchers and companies in the last decade and a considerable number of research projects have been carried out with the aim of developing solutions and assessing the potential performance of these HTHPs. This subject was specifically dealt with in the IEA Annex 35 (IEA, 2014b) dedicated to industrial heat pumps, and it is being currently continued by Annex 48 (IEA, 2016 - 2019). Several recent conferences have included this subject among their topics, and some have organized specific workshops. Among those, it is worth mentioning the Workshop 'Heating and Power from Low-Temperature Heat' in the ICR conference in Yokohama in 2015, the 12th IEA Heat Pump conference, held in Rotterdam in 2017, and the International Workshop on High-Temperature Heat Pumps, held in Copenhagen in September 2017.

6. CONCLUDING REMARKS

High-temperature heat pumps (HTHPs) are regarded as a viable and attractive solution to upgrade low-to-medium temperature industrial waste/excess heat to a useful temperature level for many industrial processes. It can be implemented in a wide range of industries as heat recovery solutions, including beverage, chemical, food, paper, leather, and textile industries. Furthermore, there are ongoing research and development activities to fully utilize the heat recovery potential of HTHPs at a heat supply temperature above 90°C. This paper has reviewed the current status and developments on HTHPs for industrial applications at delivery temperatures above 90°C. Apart from the vapor compression heat pumps (VCHPs), there are different types of heat pump technologies commercially available for high-temperature applications. The technologies are mainly absorption heat transformer (AHT) and compression-resorption heat pump (CRHP). These technologies use natural working fluid mixtures, e.g., ammonia/water and water/LiBr, which have no GWP and ODP.

The market available HTHPs based on absorption technology are mostly the single-stage water/LiBr AHT with heating capacity between 150 and 10,000 kW. The thermal COPs are in the range of 0.45 to 0.5. The heat supply temperature of these heat pumps can reach up to 160°C with a temperature lift of up to 50 K. A few heat pump applications are available for high-temperature heat supply, between 90 and 100°C, using single-effect water/LiBr AH, while there is no ammonia/water single-effect AHP for supply temperature higher than 90°C due to high operating pressure to use standard components. The current technology based on ammonia/water CRHP delivers heat up to 120°C. The obtained electrical COPs of the CRHP technology are about 2.4 (at 75 K lift), 4.3 (at 65 K lift) and 6.1 (at 22 K lift). The theoretical and experimental studies carried out by several researchers in the literature have shown that higher temperature lift (above 85 K) could be obtained using double-lift water/LiBr AHT with a potential of converting more than 30% of industrial waste/excess heat at alow-to-medium temperatures to a useful high-temperature level.

Finally, there is a strong potential for AHT and CRHP technologies for high-temperature lift and heat supply temperature above 160°C, which is the current limit for VCHP technology. Therefore, in order to capitalize these potentials, future research and development activities are mainly directed towards the following areas: *(i)* – on working fluid pairs to alleviate the drawbacks of the conventional working fluid mixtures, *(ii)* – system components size reduction so that the size and capital cost of the heat pump reduced, and *(iii)* – system (cycle) configurations to obtain higher temperature lift than the single-stage AHT, while maintaining the COP or with reasonable lower COP values.

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