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Absorption-based heat pumps for decarbonization of industrial process heating: performance, current status, and new developments

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ABSTRACT

In industry, there is a huge demand for process heat to produce, process, or finish products. Industrial process heat originates mainly from the combustion of fossil fuels, so industries need to use sustainable heat supplies if they are to reduce their carbon footprints. In this context, absorption-based heat pumps can offer a viable solution to mitigating the environmental impact of industrial heat consumption. This article reviews and discusses the state of the art of three types of absorption-based heat pumps for industrial heating applications (≥80 °C): absorption-compression heat pumps, absorption heat pumps (Type I heat pumps), and absorption heat transformers (Type II heat pumps). The water/LiBr Type I heat pump technologies currently available are restricted to a maximum heat supply temperature of 100 °C and a temperature lift up to 50 °C with thermal COPs of 1.65–1.80. The water/LiBr Type II heat pumps have a maximum heat supply temperature of 185 °C and a temperature lift of up to 50 °C with thermal COPs of 0.33–0.48. The ammonia/water absorption-compression heat pumps have a maximum heat supply temperature of 160 °C and a temperature lift of up to 110 °C with electrical COPs of 2.7–7.3. However, to fully exploit the potential of these heat pumps in process industries, research and development should focus on increasing heat supply temperature and temperature lift beyond the current limits. The use of these heat pumps to recover industrial waste heat will make a considerable contribution to the decarbonisation of the process industries.

1. Introduction

1.1. Industrial heat demand and emissions challenge

In industry, besides space heating (20–80 °C) and hot water (20–110 °C), there is a high demand for process heat (mostly > 80 °C) for producing, processing, or finishing products. The vast majority of industrial heat originates from fossil fuel combustion, and the major primary energy sources are coal and natural gas (predominantly). Hence, every year, heat contributes to the direct CO_2 emissions associated with the industry (for instance, it accounts for 36.8 % of the total energy-related emissions (12.3 Gt CO_2-eq) in 2021 [1]). Therefore, there is a pressing need in industries for a sustainable energy transition, which requires fossil-fuel sources to be replaced with renewable and low-carbon technologies and increasing energy efficiency.

Most industrial and electricity generation (e.g., power plant) processes produce a substantial amount of waste heat as a by-product [2,3]. This waste heat is freely accessible or is released into the environment, e.g., through cooling towers. Although the actual amount of industrial waste heat is difficult to quantify, several studies have estimated that between 20–50 % of the industrial energy consumed is eventually discharged as waste heat [4,5]. This heat is available at different temperature levels: 42 % below 100 °C, 20 % between 100–299 °C, and 38 % at high temperatures [3]. A substantial amount of this low-temperature waste heat (i.e., 42 % below 100 °C) cannot be recovered for reuse in other processes. For example, it is estimated that, in 2018, the EU had $8{,}774.4 \times 10^6$ GJ (2,437.3 TWh) of waste heat available at temperatures below 100 °C [4].

The waste heat generated by industries can be recovered, e.g., by the Organic Rankine Cycle (ORC) technologies [6–8]. ORC manufacturers mostly recommend that these technologies be used to recover waste heat in the range of 100–400 °C [9,10]. They can also be applied to recover waste heat at low temperatures (<100 °C) with no major design changes [11,12]. However, the recovery of waste heat by ORCs at temperatures < 85 °C is not very efficient and the economic viability of converting it into electricity must be carefully investigated [10]. On the other hand, at this temperature level (e.g., 30–70 °C), industrial waste heat is a very

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Nomenclature

Abbreviations

1 … 23	thermodynamic state points
ABS	absorber
ABS-EVA	absorber-evaporator
ACHP	absorption-compression heat pump
AHP	absorption heat pump
AHT	absorption heat transformer
COM	compressor
CON	condenser
DAHT	double absorption heat transformer
DES	desorber
DEAHT	double-effect absorption heat transformer
DH	driving heat
EVA	evaporator
GEN	generator
GTL	gross temperature lift
HP	heat pump
HTHP	high temperature heat pump
HX	heat exchanger
MIX	mixer
REC	rectifier
REV	refrigerant expansion valve
RP	refrigerant pump
RSC	refrigerant sub-cooler
SEP	separator
SEV	solution expansion valve
SHX	solution heat exchanger
SP	solution pump
SSAHT	single-stage absorption heat transformer
TAHT	triple absorption heat transformer
TSAHT	two-stage absorption heat transformer
VCHP	vapour compression heat pump

Variables

COP	coefficient of performance (−)
h	specific enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa and bar)
pr_{com}	compressor pressure ratio (−)
$\dot{Q}$	heat flow rate (kW)
s	specific entropy (kJ/kg·K)
t or T	temperature (°C or K)
$\overline{T}$	entropic average temperature (K)
$\dot{W}$	electrical/mechanical power (kW)
X	LiBr mass fraction (kg/kg)
z	ammonia mass fraction (kg/kg)

Subscripts

II	second-law
abs	absorber
ACHP	absorption-compression heat pump
AHP	absorption heat pump
AHT	absorption heat transformer
amb	ambient
com	compressor
con	condenser
des	desorber
dh	driving heat
el	electrical
eva	evaporator
HP	heat pump
hr	heat rejection
hs	heat source
in	inlet or net input
out	outlet or net output
sp	solution pump
sup	heat supply
th	thermal

Superscripts

abs	absorber
app	approach
con	condenser
hs	heat source
hr	heat rejection
min	minimum
max	maximum
sup	supply

Greek symbols

Δ	difference
η	efficiency
ε	effectiveness

valuable heat source for heat pumps because its temperature is significantly higher than ambient air, ground, and nearby natural water sources [13]. The availability of low-temperature waste heat (below 100 °C) within or in close vicinity to an industrial plant and the demand for process heat (>80 °C) signifies that heat pumps can be used to enhance energy utilization efficiency and reduce CO_2 emissions.

1.2. Industrial heat pump technologies

Heat pumps are well-known for space heating and hot water supply in residential and commercial buildings [14–16]. However, heat pumps are used much less in the process industry sector. In the last decade, industrial heat pumps have attracted the interest of researchers, companies, and international organizations, particularly in projects such as the IEA heat pump program (IEA-HPP)-IETS Annex 35/13 (2010–2014) [17], Annex 48 (2016–2019) [18], and Annex 58 (2020–2023) [19]. Industrial heat pumps are often referred to as high-temperature heat pumps (HTHPs) because of the supply (sink) temperature; however, there is no consistent definition of the temperature range in the literature [13]. Based on the IEA-HPT (Annex 58), HTHPs are defined as devices that supply a part of their main output at temperatures above 100 °C [20]. In this article, heat pumps with a supply temperature above (or equal to) 80 °C are considered to be industrial heat pumps because (i) most residential heat pumping technologies operate below 60–70 °C for sanitary hot water production (these temperatures inhibit the growth of Legionella bacteria) and (ii) process heat is largely delivered above 80 °C.

The industrial heat pumps can be classified based on system type (i.e., open or closed), technology and its subtype, and type of driving energy input (mechanical work/electricity or heat) as depicted in Fig. 1. It should be noted that there are other types of sorption heat pumps (e.g., adsorption heat pumps, Fig. 1) but they are mainly used for hot water production and space heating applications [21,22].

Industrial heat pumps based on the mechanical vapour compression process are the heating option that has mostly been studied, and the reader is referred to Arpagaus et al. [13,23,24], who report detailed technical and economic data of existing compression heat pump technology, and others ([1,25,26]). Multi-temperature applications of work-

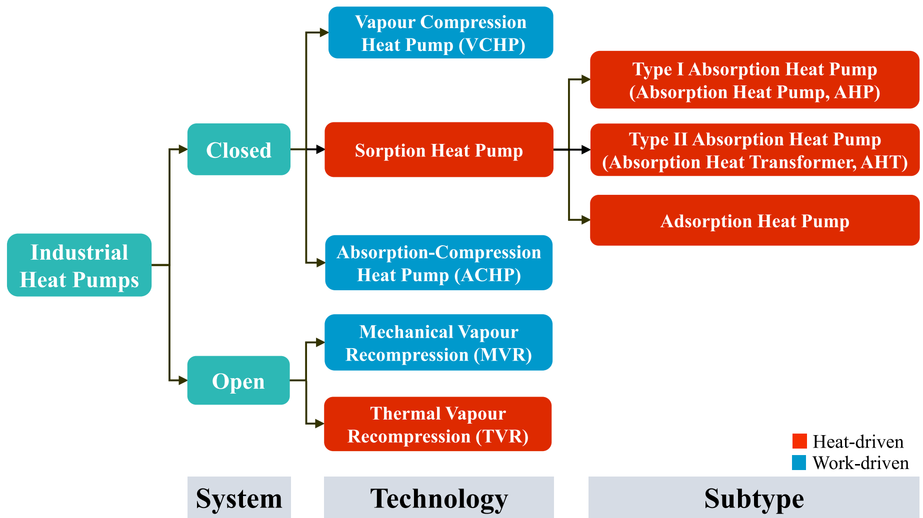

Fig. 1. Typical classification of industrial heat pumps.

driven heat pumps and refrigerants have been discussed in Ref. [23]. The use of natural refrigerants (e.g., R717, R744, R718, R600, and R290) for industrial heat pump applications has been reviewed by Bamigbetan et al. [27], who discuss the technical challenges of implementing HTHPs, and possible innovative solutions to address these challenges including working fluids, development of components, and system optimization. In industrial processes, the HTHPs that use natural working fluids (refrigerants) have proved to be a potential environmentally friendly solution to recovering waste heat. Zhang et al. (2016) [28] discussed research and the development of industrial heat pumps in China. They focused on three industrial fields- wastewater sludge drying, crude oil heating, and process heating in the printing and dying industry- and reviewed research progresses into refrigerants and different types of heat pump systems. Moreover, Chua et al. [29] reviewed and discussed performance improvement methods (e.g., multistage cycles and hybrid heat pump systems) and their applications in selected industries. Further, Ayou et al. [30] gave an overview of the current status of HTHPs and research developments. They also discussed different types of HTHP systems and recent advances into compressor technologies and working fluids for HTHPs based on vapour compression cycles.

1.2.1. *Absorption-based heat pump technologies*

There are two types of sorption heat pumps (Fig. 1, liquid-sorption heat pumps): Type I heat pumps (absorption heat pumps, AHPs) for heat amplification and Type II heat pumps (absorption heat transformers, AHTs) for temperature amplification (i.e., temperature boosting). There is also a hybrid heat pump that combines vapour absorption and vapour compression systems and technologies, which in this article is referred to as an absorption-compression heat pump (ACHP, Fig. 1). Recently, an ACHP using ammonia/water mixture has been optimized with wet compression for applications with large temperature glides on the heat sink side [31]. The use of a twin screw compressor with weak ammonia/water solution injection (ranging from 0.015 to 0.25 kg/s) effectively reduces the compressor discharge temperature from 139 °C to 122 °C and increases the heat sink glide from 28 °C to 48 °C [31]. The preliminary results showed a heating capacity of 50 kW and a cooling capacity of 26 kW. In addition to ACHPs, it is important to note that Type I AHPs are also capable of simultaneously providing heating and cooling outputs at different temperature levels.

Among the various sectors of the process industry, the food and beverage manufacturing sector has considerable potential for the integration and deployment of absorption-based heat-pumping technologies. For example, in the dairy processing industry, several unit processes require heating at temperatures below 200 °C, including milk pasteurization (71–74 °C), sterilization (109–115 °C), and ultra-high-temperature (UHT) processing (135–150°C) [32–34]. Also, in beer brewing, heating in the range of 35–85 °C is necessary for processes such as wort production and service of warm water, which includes cleaning operations like CIP (Clean-in-Place), as well as the cleaning of bottles and kegs [34]. These temperature requirements align well with the capabilities of absorption-based heat pump technologies, making them ideal for such applications.

To the best of our knowledge, comprehensive reviews of absorption-based heat pumps tailored to industrial heating applications (≥80 °C) are scarce. Existing studies often focus on vapour compression heat pumps or low-temperature absorption systems for residential use, leaving a knowledge gap in the systematic evaluation of AHPs, AHTs, and ACHPs for high-temperature industrial process heating contexts. To address this gap, this review synthesizes the performance, current commercial status, and emerging developments of these technologies. Our research strategy involved a systematic literature search using literature databases, with keywords including “absorption heat pump”, “absorption heat transformer”, “absorption-compression heat pump”, “industrial process heating”, “high-temperature heat pump”, and “decarbonization”. We prioritized peer-reviewed articles, technical reports, and manufacturer data published after 2010 to capture recent advancements, supplemented by key foundational simulation works. The scope was narrowed to systems delivering heat ≥ 80 °C, aligning with industrial process needs. The present review article focuses on the current state of the art and new trends/developments in absorption-based heat pumps for industrial process heating applications.

This work aims to bridge the gap by providing a detailed analysis of absorption-based heat pumps, focusing on their thermodynamic performance, commercial deployment across industrial sectors, and innovative research trends. Unlike prior reviews, it integrates theoretical simulations, real-world case studies, and future development pathways, offering a holistic perspective on their role in industrial decarbonization. The paper is structured as follows: Section 2 describes the heat pump technologies and their simulated performance; Section 3 reviews commercial products; Section 4 examines global deployment cases; Section 5 discusses research projects and new developments; Section 6 discusses and summarizes key aspects; and Section 7 concludes with recommendations for advancing these technologies.

2. Heat pump description and simulated performance

2.1. Heat pump description

2.1.1. Absorption-compression heat pumps (ACHPs)

The ACHPs, also known as compression/resorption heat pumps in the literature [35,36], combine absorption and vapour compression heat pumping technologies. The ACHPs benefit from the best features of each type of technology, which are higher performance (i.e. higher COP) of the VCHPs and large temperature lifts and temperature gliding of sorption heat pumps (i.e. AHPs and AHTs). Similar to absorption cycles, ACHP cycles need a zeotropic mixture comprising a refrigerant and an absorbent which are characterized by a large difference in boiling point. In general, most of the working fluid mixtures used in absorption cycles can also be applied in ACHP cycles [37,38]. However, the thermo-physical properties of these mixtures must carefully be evaluated under different aspects according to the mechanical compression of the vapour. Typically, an ammonia/water mixture is used as a working fluid in ACHP systems. However, other working fluid mixtures are also investigated in the literature [39–42].

Fig. 2(a) depicts a two-temperature level work-driven heat pump such as ACHPs. Fig. 2(b) shows the cycle layout of a single-stage ACHP, which incorporates a solution circuit between the absorber (also denoted as resorber [35]) and desorber known as a resorption circuit. ACHPs consist of an absorber, which has an adiabatic (mixer) and non-adiabatic (heat exchanger) sections, a compressor, a desorber, which consists of the heat exchanger and separator, solution heat exchanger, solution expansion valve, and solution pump. In the literature, this type of heat pump is also known as a vapour compression cycle with a solution circuit [40] or a hybrid absorption-compression heat pump [38].

Compared with the VCHP, ACHP has several advantages which are (i) increased COP by using the gliding temperatures in absorber and desorber, (ii) reduction of pure refrigerants saturation pressures (at a given temperature) caused by the solution in the refrigerant cycle which allows the resorption temperature of the mixture (e.g. ammonia/water) to be higher than the critical temperature of the pure refrigerant (ammonia), and (iii) capacity adjustment by changing the concentration of the working fluid mixture. An ammonia/water ACHP is a promising technology for industrial applications using existing standard commercial components such as plate heat exchangers and ammonia compressors [38].

2.1.2. Absorption heat pumps (Type i HPs)

Fig. 3(a) shows a three-temperature level heat-driven heat pump (AHP). The single-effect AHPs shown in Fig. 3(b) and 3(c) are the basic configurations of Type I HP technologies using water/LiBr and ammonia/water mixtures, respectively. The water/LiBr AHP depicted in Fig. 3(b) has seven main components: an absorber (ABS), a condenser (CON), a desorber (DES), an evaporator (EVA), a solution heat exchanger (SHX), a solution pump (SP), and expansion valves (SEV and REV). The ammonia/water AHP (Fig. 3(c)) has two additional components: a rectifier (REC) and a refrigerant sub-cooler (RSC) because of the volatility of the absorbent (water) and the high vapour pressure of the refrigerant (ammonia) which allows internal heat recuperation in the refrigerant stream, respectively [43]. The AHP's heat supply stream (Fig. 3(b) and 3(c)) collects heat from the ABS and CON, which can be connected in a series or parallel flow arrangement. The series connection produces the most heated supply stream compared to the parallel connection of the ABS and CON.

2.1.3. Absorption heat transformers (Type II HPs)

An absorption heat transformer (AHT), which is based on the reverse operation of AHP (Type I HP), enables heat at intermediate temperature (T_{hs}) to drive the absorption cycle and supply heat at high temperature (T_{sup}) as illustrated in Fig. 4(a). In AHTs, the temperature increases ($\Delta T_{lift} = T_{sup} - T_{hs}$) is achieved by degrading a fraction of the heat at an intermediate temperature level to low temperature (T_{hr}, $\Delta T_{thrust} = T_{sup} - T_{hr}$). The cycle layout of the water/LiBr and ammonia/water single-stage AHTs are depicted in Fig. 4(b) and Fig. 4(c), respectively.

2.2. Simulated heat pump performance

The steady-state performance simulation models of absorption-based heat pumps (ACHP, AHP, and AHT illustrated in Fig. 2, Fig. 3, and Fig. 4) are based on the mass and energy conservation of the individual component and the overall heat pump, with the heat transfer equations for each component, implemented in the EES (Engineering Equation Solver) software [44]. Also, the 2nd Law of thermodynamics is ensured in each heat pump component model. Water/LiBr and ammonia/water mixtures have been used in the theoretical performance simulation as they are used in commercial heat pumps. The correlations of water/LiBr solution and ammonia/water mixture properties were taken from SSCLIBR property library (available in EES software) and Tillner-Roth and Friend [45], respectively. The properties of water, used as an external heat carrier circuit, were calculated using the IAPWS-IF95

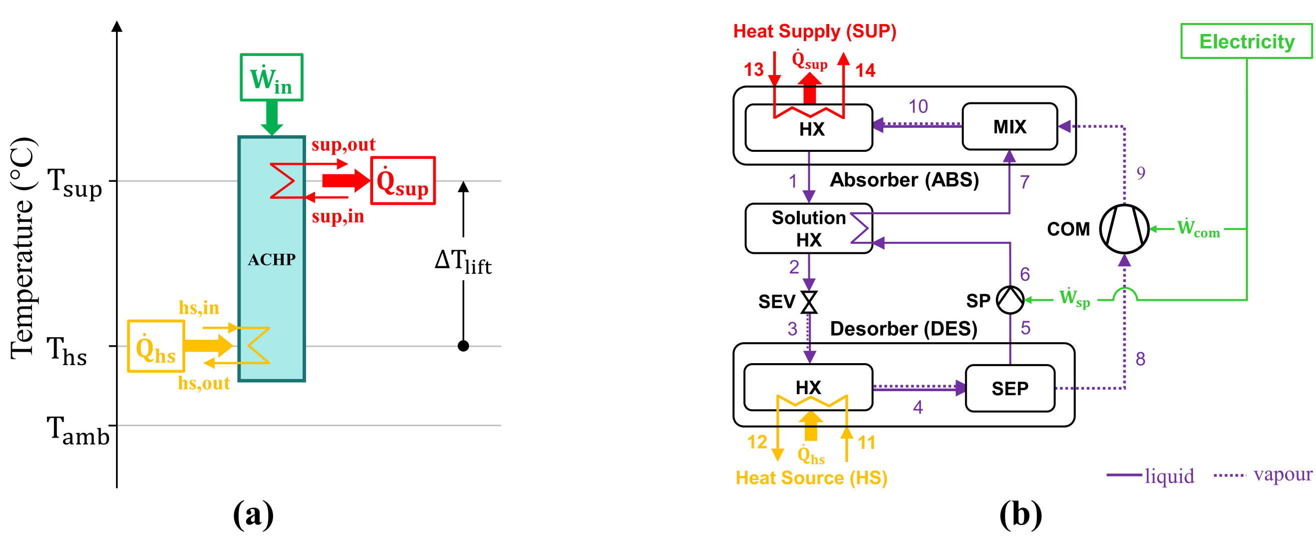

Fig. 2. (a) Two temperature level work-driven heat pump and **(b)** Cycle layout of single-stage ACHP. Note: COM = compressor. HX = heat exchanger. MIX = mixer (adiabatic absorption). SEP = separator. SEV = solution expansion valve. SP = solution pump.

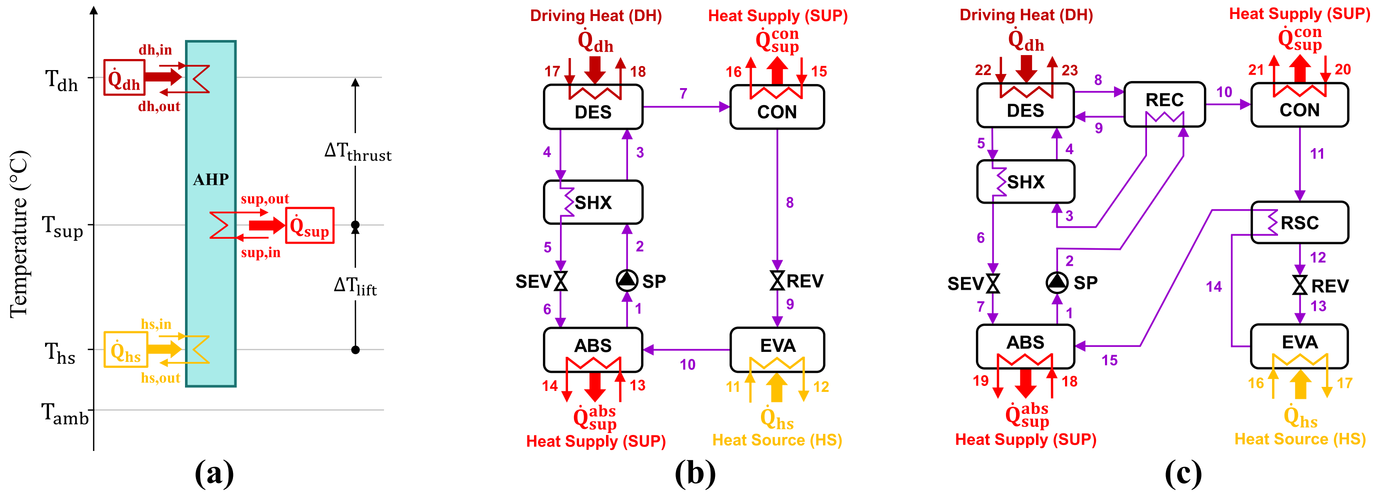

Fig. 3. **(a)** Three temperature level heat-driven Type I HPs (AHPs), **(b)** Cycle layout of single-effect water/LiBr AHP, and **(c)** Cycle layout of single-effect ammonia/water AHP. Note: ABS = absorber. CON = condenser. DES = desorber. EVA = evaporator. REC = rectifier. REV = refrigerant expansion valve. RSC = refrigerant sub-cooler. SEV = solution expansion valve. SHX = solution heat exchanger. SP = solution pump.

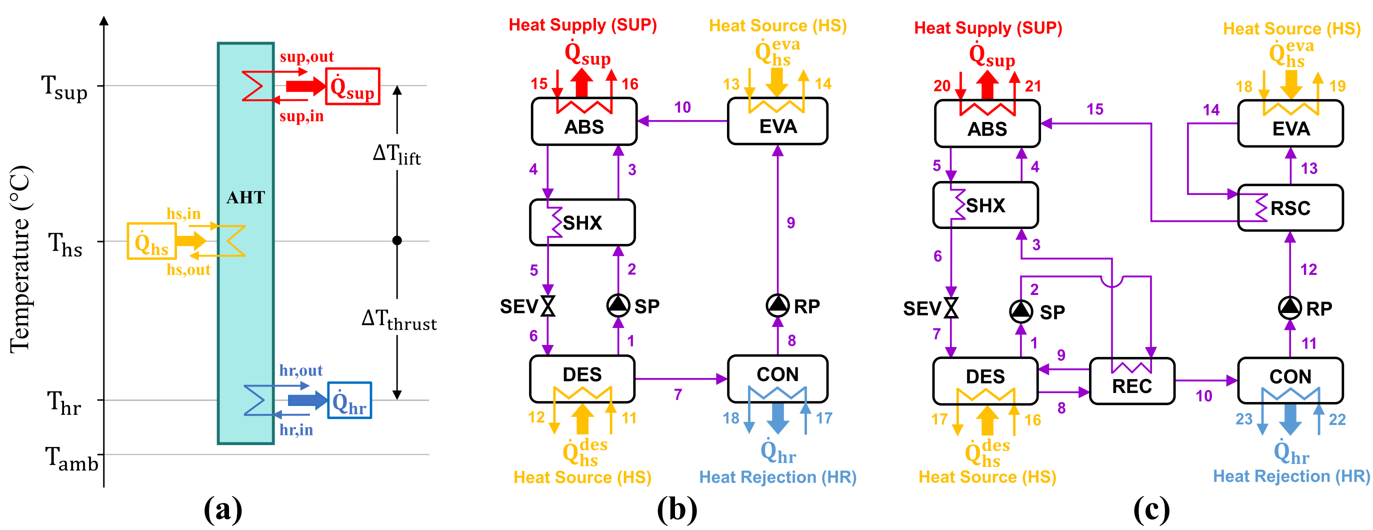

Fig. 4. **(a)** Three temperature level heat-driven Type II HPs (AHTs), **(b)** Cycle layout of single-stage water/LiBr AHT, and **(c)** Cycle layout of single-stage ammonia/water AHT.

values.

The following commonly used modelling assumptions, for absorption-based heat pumps, are made [38,43]: • steady-state conditions are considered; • no heat losses to the environment; • potential and kinetic energy effects are neglected; • pressure drops and fluid leakage in pipelines are neglected; • liquid solution leaving the ABS and DES are at saturated state at their corresponding temperature and pressure; • the liquid refrigerant leaving the CON is saturated; • saturated vapour leaving the EVA of the water/LiBr AHP and AHT while partial vaporization is allowed in the EVA (with fixed temperature glide) of the ammonia/water AHP and AHT. • the expansion processes in the SEV and REV are isenthalpic; • the rectified vapour and liquid reflux leaving the REC of the ammonia/water AHP and AHT are saturated; • the ACHP's mechanical compressor (COM) operates adiabatically with constant isentropic and volumetric efficiencies; • the SHX and RHX have a constant effectiveness value; • the SP has constant isentropic efficiency.

The generic equations of mass and energy conservations, based on the above assumptions, for each heat pump component (unit, u) are expressed by Eqs. (1) – (4), respectively:

Overall mass balance for unit (u):

$$\sum_{i\in IN(u)} \dot{m}_i - \sum_{i\in OUT(u)} \dot{m}_i = 0 \tag{1}$$

where $\dot{m}_i$ (kg/s) is the mass flow rate of stream i, $IN(u)$ denotes the set of inflowing streams into the unit, and $OUT(u)$ indicates the set of outgoing streams from the unit.

LiBr mass balance for unit (u) of the water/LiBr AHP (Fig. 3(b)) and water/LiBr AHT (Fig. 4(b)):

$$\sum_{i\in IN(u)} X_i\dot{m}_i - \sum_{i\in OUT(u)} X_i\dot{m}_i = 0 \tag{2}$$

where X_i (kg/kg) is the LiBr mass fraction of stream i.

Ammonia mass balance for unit (u) of the ACHP (Fig. 2(b)), ammonia/water AHP (Fig. 3(c)) and ammonia/water AHT (Fig. 4(c)):

$$\sum_{i\in IN(u)} z_i\dot{m}_i - \sum_{i\in OUT(u)} z_i\dot{m}_i = 0 \tag{3}$$

where z_i (kg/kg) is the ammonia mass fraction of stream i.

Energy balance for unit (u):

$$\sum_{i\in IN(u)} \dot{m}_i h_i - \sum_{i\in OUT(u)} \dot{m}_i h_i + \dot{Q}_u - \dot{W}_u = 0 \tag{4}$$

where h_i (kJ/kg) is the specific enthalpy of stream i, and $\dot{Q}_u$ (kW) and $\dot{W}_u$ (kW) are the heat and work flow rates, respectively, into or out of the control volume for unit u. Heat flows into a unit and work done by a unit are taken as positive in Eq. (4).

The COM electrical power consumption of the ACHP ($\dot{W}_{com,el}$, kW$_{el}$) is calculated using Eq. (5).

$$\dot{W}_{com,el} = \frac{\dot{m}_{com}\left(h_{com,out} - h_{com,in}\right)}{\eta_m} \tag{5}$$

where $\dot{m}_{com}$ (kg/s) is mass flow rate of vapour through the COM, $h_{com,in}$ and $h_{com,out}$ (kJ/kg) are the COM suction (inlet) and discharge (outlet) vapour enthalpies, and η_m is the electrical motor efficiency.

The isentropic efficiency of the COM (η_{com}^{ise}) is defined as:

$$\eta_{com}^{ise} = \frac{h_{com,out}^{ise} - h_{com,in}}{h_{com,out} - h_{com,in}} \tag{6}$$

where $h_{com,out}^{ise}$ (kJ/kg) is the ideal outlet enthalpy with an isentropic compression process. The electrical power consumed by the SP ($\dot{W}_{sp,el}$, kW$_{el}$) is calculated by:

$$\dot{W}_{sp,el} = \frac{\dot{m}_{sp}\dot{v}_{sp,in}\left(P_{high} - P_{low}\right)}{\eta_{sp}^{ise}\eta_m} \tag{7}$$

where $\dot{m}_{sp}$ (kg/s) is the flow rate through the SP, $\dot{v}_{sp,in}$ (m^3/kg) is the specific volume at the SP inlet, P_{low} and P_{high} (kPa) are the pressure at the SP inlet and outlet, and η_{sp}^{ise} is the SP isentropic efficiency. The SP isentropic efficiency (η_{sp}^{ise}) is defined as:

$$\eta_{sp}^{ise} = \frac{h_{sp,out}^{ise} - h_{sp,in}}{h_{sp,out} - h_{sp,in}} \tag{8}$$

where $h_{sp,in}$ and $h_{sp,out}$ (kJ/kg) are the SP inlet and outlet working fluid pair liquid enthalpies, and $h_{sp,out}^{ise}$ is the ideal outlet stream enthalpy with an isentropic pumping process (kJ/kg).

The ideal coefficient of performance of the work-driven heat pump (ACHP, COP_{ACHP}^{ideal}) and heat-driven heat pumps (AHP and AHT, COP_{AHP}^{ideal} and COP_{AHT}^{ideal}) are computed by Eqs. (9)–(11) when operating at two and three temperature levels, respectively.

$$COP_{ACHP}^{ideal} = \frac{T_{sup}}{T_{sup} - T_{hs}} \tag{9}$$

where T_{sup} and T_{hs} (K) are heat supply and source temperatures, respectively.

$$COP_{AHP}^{ideal} = \frac{(T_{dh} - T_{hs})}{T_{dh}} \frac{T_{sup}}{(T_{sup} - T_{hs})} \tag{10}$$

$$COP_{AHT}^{ideal} = \frac{(T_{hs} - T_{hr})}{T_{hs}} \frac{T_{sup}}{(T_{sup} - T_{hr})} \tag{11}$$

where T_{dh} and T_{hr} (K) are driving heat and heat rejection temperatures, respectively. For the heat pumps that interact with surroundings at variable temperatures (i.e., heat is added and rejected at variable temperatures), the isothermal temperatures in Eqs. (9)–(11) must be replaced by the associated entropic average temperature ($\overline{T}$, in K) of each heat carrier stream ($\overline{T}_{dh}$, $\overline{T}_{hs}$, $\overline{T}_{hr}$, and $\overline{T}_{sup}$) is given by Eq. (12) [46].

$$\overline{T} = \frac{h_{in} - h_{out}}{s_{in} - s_{out}} \tag{12}$$

where h_{in} (kJ/kg) and s_{in} (kJ/kg K) and h_{out} (kJ/kg) and s_{out} (kJ/kg K) are the stream's specific enthalpy and entropy at the inlet and outlet. Further, for the constant specific heat capacity of the fluid, the entropic average temperature can be expressed only in terms of temperatures as: $(T_{in} - T_{out})/Ln(T_{in}/T_{out})$. Then, Eq. (12) retains the simplicity of the constant temperature approach (in Eqs. (9)–(11)) but makes it applicable to varying temperature processes. However, the real COP of these heat pumps is limited (i.e., $COP < COP^{ideal}$) due to the inherent internal and external irreversibilities of the heat pump system [43,47].

The actual $COPs$ of the work-driven heat pump (COP_{ACHP}) and heat-driven heat pumps (COP_{AHP} and COP_{AHT}) are given by Eqs. (13)–(15).

$$COP_{ACHP} = \frac{\dot{Q}_{sup}}{\dot{W}_{in}} (> 1.0) \tag{13}$$

where $\dot{Q}_{sup}$ (kW) is heat supply rate and $\dot{W}_{in}$ (kW) is the driving input work rate (or input electrical power).

$$COP_{AHP} = \frac{\dot{Q}_{sup}}{\dot{Q}_{dh}} (> 1.0) \tag{14}$$

$$COP_{AHT} = \frac{\dot{Q}_{sup}}{\dot{Q}_{hs}} (< 1.0) \tag{15}$$

where $\dot{Q}_{dh}$ (kW) is the driving heat rate and $\dot{Q}_{hs}$ (kW) is the heat source rate. Thus, the ratio of the actual-to-ideal COP of the heat pumps (second-law efficiency, $\eta_{II,HP}$, Eq. (16)) is a useful parameter for comparing the performance of different heat pump technologies. It also indicates potential improvement possibilities.

$$\eta_{II,HP} = \frac{COP_{HP}}{COP_{HP}^{ideal}} \tag{16}$$

Another key parameter for evaluating the performance of heat pumping technologies is the temperature lift (ΔT_{lift}), which is expressed as: $T_{sup,out} - T_{hs,in}$.

To identify the operational limits of considered absorption-based HP cycles in this section and compare their performance, a steady-state thermodynamic simulation was carried out for each basic HP cycle type (i.e. ACHP, AHP, and AHT shown in Figs. 2–4). The performances of these HPs were compared from the perspective of the first law and second law of thermodynamics (using electrical/thermal heating COP, Eqs. (13)–(15), and $\eta_{II,HP}$ given by Eq. (16).

2.2.1. Absorption-compression heat pumps (ACHPs)

The operational range of the ammonia/water ACHP is mainly constrained by the limitations of market-available system components, especially the compressor (discharge temperature and pressure, lubricants, etc.). The operational envelope of a single-stage ammonia/water ACHP is shown in Fig. 5(a–d) with the input conditions listed in Table 1. The design constraints are also given in Table 1.

For partial vaporization in the desorber to occur, the desorber pressure (P_{des}) must be between the dew and bubble pressures at the strong solution concentration ($z_s = z_1$) and desorber temperature (t_4, Fig. 2(b)). Additionally, the desorber is constrained to operate above 1.0 bar to circumvent a sub-atmospheric working condition. The maximum heat supply temperature (t_{14}^{max}, Fig. 2(b)) of the heat pump is obtained by supposing a reasonable minimum temperature difference ($\Delta T_{abs}^{min} = 5\,°C$) with the maximum temperature inside the absorber (i.e., $t_{14}^{max} = t_{10} - \Delta T_{abs}^{min}$).

Fig. 5(a–d) depicts the operational envelope of the single-stage ammonia/water ACHP (Fig. 2). The technological design constraints (Table 1) related to minimum and maximum ACHP pressures, maximum compressor discharge temperature, and minimum allowed ammonia mass fraction in the vapour stream passing through the compressor are

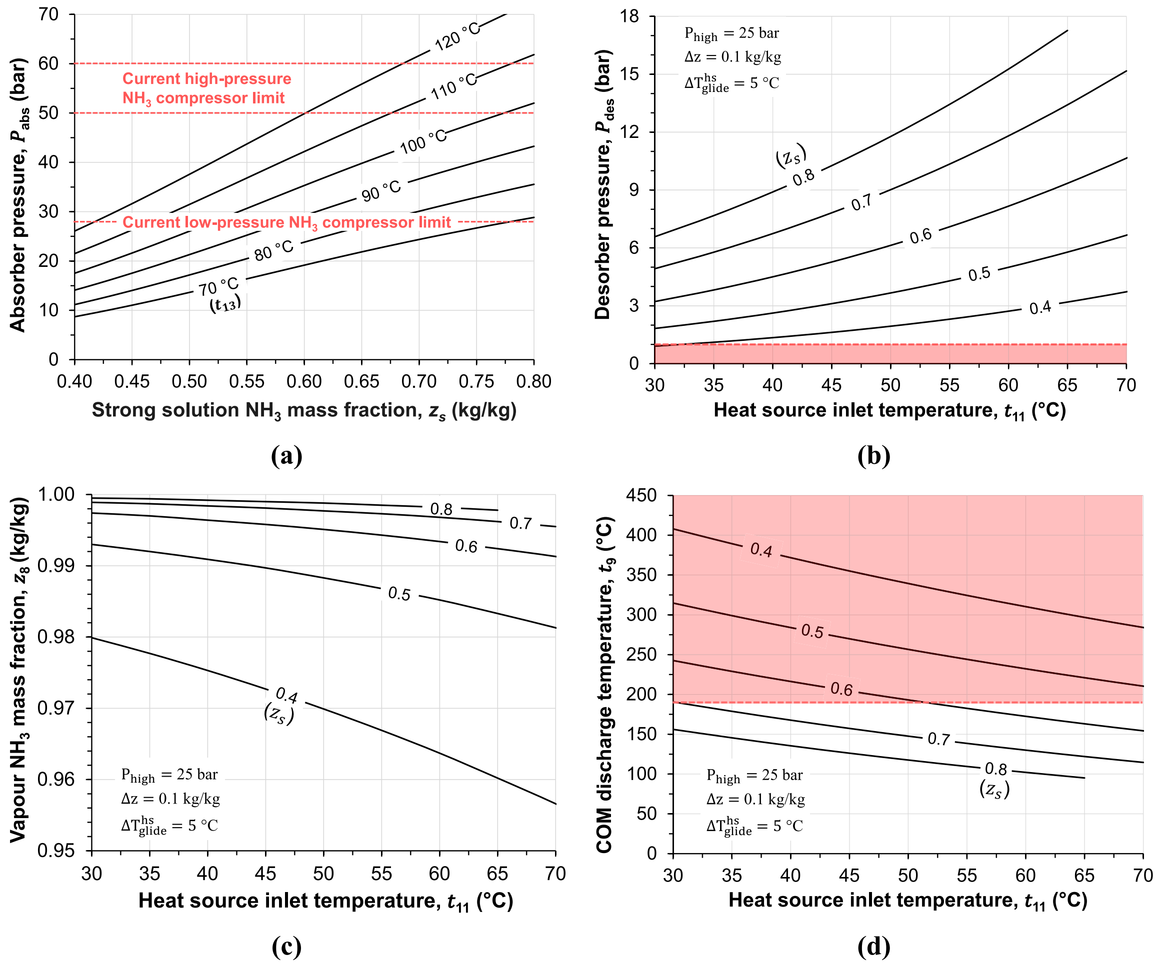

Fig. 5. Operational envelope of single-stage ammonia/water ACHP (Fig. 2(b)) based on input operating condition and design parameters listed in Table 1. **(a)** absorber (system high) pressure, **(b)** desorber (system low) pressure, **(c)** vapour stream ammonia (NH_3) concentration (z_8), and **(d)** compressor (COM) discharge temperature (z_9).

also shown in Fig. 5(a–d).

In Fig. 6(a), the maximum temperature lift ($\Delta T_{lift} = t_{14}^{max} - t_{11}$) and electrical COP ($COP_{ACHP}$) are depicted as a function of heat source inlet temperature between 30 °C and 70 °C for various values of solution circuit concentration difference (i.e. Δz = 0.05, 0.10, 0.15, and 0.20) and 0.7 kg/kg strong solution ammonia mass fraction. In this range, the corresponding second-law efficiency ($\eta_{II,ACHP}$) and volumetric heating capacity (*VHC*) are illustrated in Fig. 6(b).

When the heat source inlet temperature increases the COP_{ACHP} also increases whereas the $\eta_{II,ACHP}$ decreases at each concentration difference (Δz). The maximum heat supply temperature is almost constant despite the heat source inlet temperature variation at each Δz (Fig. 6), which is about 88 °C ($\Delta z = 0.05$ and $z_s = 0.6$), 95 °C ($\Delta z = 0.10$ and $z_s = 0.6$), 103 °C ($\Delta z = 0.15$ and $z_s = 0.6$). In this range, temperature lift is between 18–48 °C, 25–43 °C, and 33–38 °C, respectively. In the case of $z_s = 0.7$, the maximum heat supply temperature is about 76 °C (Δz = 0.05), 81–82 °C (Δz = 0.10), 87–89 °C (Δz = 0.15), and 95–96 °C (Δz = 0.20). The corresponding temperature lift is between 6–46 °C, 11–51 °C, 17–49 °C, and 25–44 °C. The electrical COP and $\eta_{II,ACHP}$ of ACHP based on the input conditions and design constraints (Table 1), for $z_s = 0.6$, are between: 2.7–6.3 and 30.9–35.8 % (Δz = 0.05); 3.6–5.7 and 33–39.5 % ($\Delta z = 0.10$); and 4.3–4.8 and 33.0 %–35.5 (Δz = 0.15). In the case of $z_s = 0.7$, the COP_{ACHP} and $\eta_{II,ACHP}$ are between: 3.0–12.0 and 20.3–39.3 % (Δz = 0.05); 3.2–9.7 and 23.6–43.8 % (Δz = 0.10); 3.5–7.6 and 25.3–42.8 % (Δz = 0.15); and 4.0–6.1 and 26.6–38.5 % (Δz = 0.20). In Fig. 6(a–d), the temperature range of the heat source is limited due to the maximum compressor discharge temperature set at 190 °C. The rise of this temperature limit (>190 °C) because of advancements in compressor technology enables to increase in the

Table 1
Input modelling parameters of single-stage ammonia/water ACHP (Fig. 2(b)).

Parameter and unit	Value/ Range
Heat source inlet temperature, t_{11} (°C)	30–70
Strong solution ammonia mass fraction, z_s (kg ammonia/kg solution)	0.40–0.80
Concentration difference, Δz (kg ammonia/kg solution)	0.05–0.20
High (ABS) pressure, P_{abs} (bar)	25
Approach temperature difference for ABS and DES, $\Delta T^{app}_{abs/des}$ (°C)	5
Heat source temperature glide, ΔT^{hs}_{glide} (°C)	5
Effectiveness of SHX, ε_{shx} (%)	85
COM isentropic efficiency, η_{com} (%)	75
SP isentropic efficiency, η_{sp} (%)	75
Electrical efficiency of COM and SP motors, $\eta_{el,com/sp}$ (%)	90
Design constraints based on current COM technology [48,49]	
Maximum system high (ABS) pressure, $P_{abs,max}$ (bar)	28[a], (50/60)[b]
Maximum COM discharge temperature (°C)	190[c]
Maximum amount of water vapour allowed in the COM (%)	5[c]

Note: $\Delta z = z_s - z_w$. z_w = weak (in ammonia) solution ammonia mass fraction. $\Delta T^{app}_{abs} = t_1 - t_{13}$. $\Delta T^{app}_{des} = t_{11} - t_4$. $t_5 = t_8 = t_4$ (adiabatic vapour-liquid separation). [a] low-pressure ammonia compressor. [b] high-pressure ammonia compressor. [c] for both low- and high-pressure ammonia compressors.

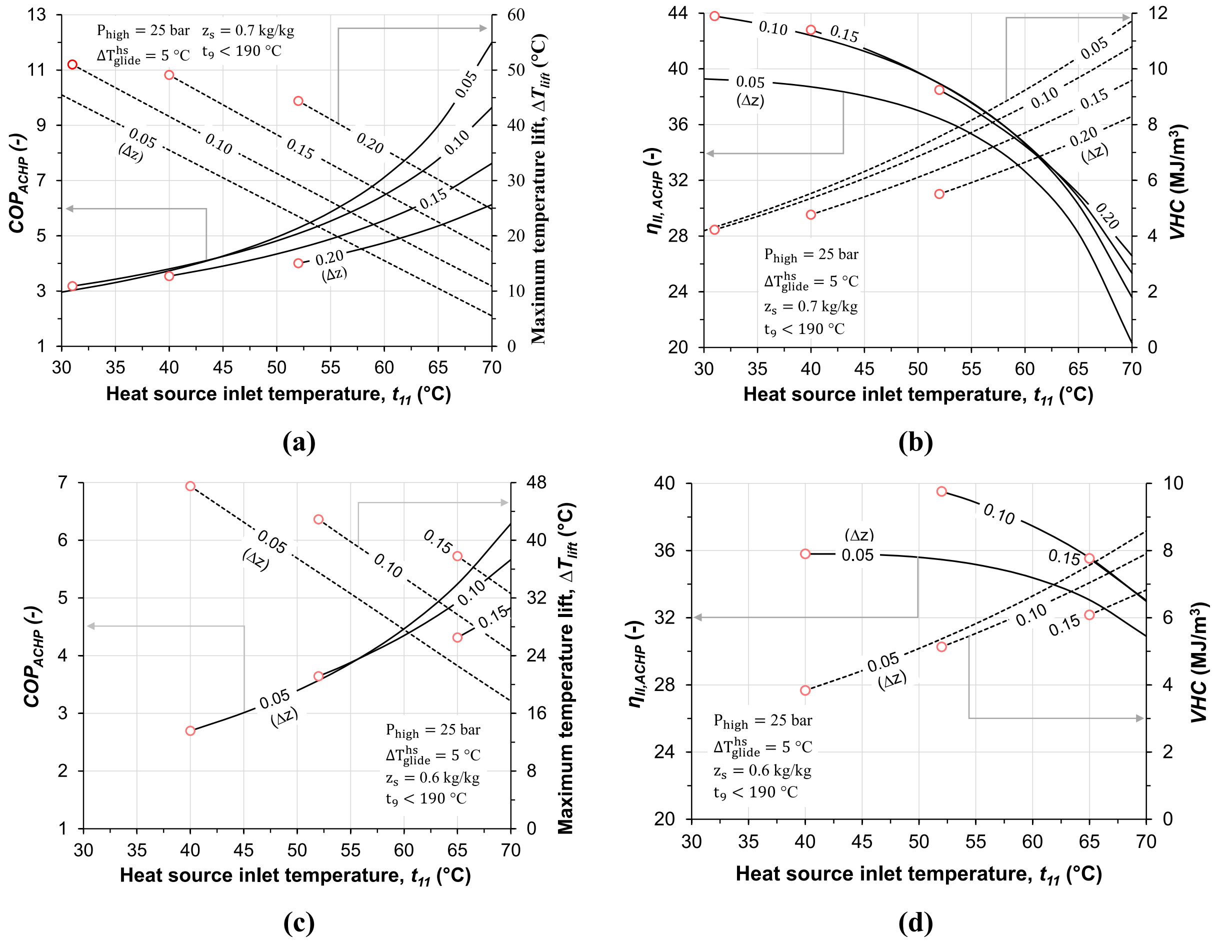

Fig. 6. **(a)** COP_{ACHP} and maximum temperature lift (ΔT_{lift}) at $z_s = 0.7$, **(b)** $\eta_{II,ACHP}$ and VHC at $z_s = 0.7$, **(c)** COP_{ACHP} and maximum temperature lift (ΔT_{lift}) at $z_s = 0.6$, and **(d)** $\eta_{II,ACHP}$ and VHC at $z_s = 0.6$ of a single-stage ammonia/water ACHP as a function of heat source inlet temperature (t_{11}) at several concentration differences (Δz) of the solution circuit.

temperature lift of the heat pump.

2.2.2. Absorption heat pumps (AHPs)

The operational envelope of single-effect AHPs (shown in Fig. 3(b) and 3(c)) for recovering low-grade waste heat (<80 °C) for process heat supplied at high temperatures (≥ 80 °C) is obtained using the input operating and design parameters listed in Table 2. The ammonia/water AHP (Fig. 3(c)) is not usually desired for high-temperature heat pumping applications because of high operating pressures (e.g., at a temperature > 80 °C, the corresponding saturated liquid pressure is > 40 bar for an ammonia/water mixture with ammonia composition of 98 % on mass base). Hence, the ammonia/water AHP is more appropriate for low-temperature heat pumping applications (e.g., residential heat pumps or process applications, which require low heat supply temperatures [<80 °C]); especially, when standard heat pump components are used.

Table 2
Input modelling parameters of single-effect AHPs (Fig. 3(b) and Fig. 3(c)).

Parameter and unit	Value/ Range
Heat source inlet temperature, t_{11} (Fig. 3(b)) and t_{16} (Fig. 3(c)) (°C)	30–70
Heat supply outlet temperature, t_{14}/t_{16} (Fig. 3(b)) and t_{19}/t_{21} (Fig. 3 (c)) (°C)	≥ 80
Heat source and supply temperature gliding, ΔT^{hs}_{glide} and ΔT^{sup}_{glide} (°C)	10
Approach temperature difference for ABS, CON, DES, and EVA, ΔT^{app}_{u} (°C)	5
Effectiveness of internal heat recuperators, ε_{ihx} (%) [43]	64[a], 80[b]
Solution pump efficiency, η_{sp} (%)	70
Ammonia mass fraction of purified vapour leaving the rectifier (Fig. 3 (c)), z_{10} (kg/kg) [43]	0.9996[b]

Note: [a] water/LiBr AHP; [b] ammonia/water AHP.

The working range of water/LiBr AHP is restricted by the characteristics of the water/LiBr solution: its limited solubility range (i.e., crystallization), instability at high temperatures, and the fact that it corrodes metal, which is often used to make the AHP components (e.g., carbon steel, copper, and copper alloy). For example, ordinary carbon steel has an almost constant corrosion rate to water/LiBr solution at temperatures below 165 °C [50] but metal materials are corroded even more at high temperatures (e.g., >200 °C) and high LiBr concentrations. This has been observed in the practical operation of a triple-effect water/LiBr chiller at temperatures above 180 °C, which is limited by problems of corrosion and thermal stability. Like air-cooled water/LiBr chillers, water/LiBr AHPs are also vulnerable to the problem of crystallization [51]. The mass fraction of LiBr should be kept under 70 % so that the water/LiBr solution can remain miscible [52] as the limit for the LiBr mass fraction if the AHP is to operate safely. Also, the AHP systems should limit the maximum LiBr concentration to 65 % (on mass base) to avoid problems of crystallization [53,54].

Accordingly, in addition to corrosion problems, water/LiBr AHPs need to overcome the crystallization barrier so that the operational envelope of the water/LiBr AHP can be extended to deliver process heat at temperatures above 100 °C. Concerning the ammonia/water AHP (Fig. 3(c)), for the design parameters listed in Table 2 and heat source inlet and heat supply outlet temperatures of 50 °C and 80 °C, the minimum driving heat temperature required to activate the heat pump is about 139 °C. However, the high pressure in the heat pump is about 43.2 bar.

The thermal COP_{AHP}, $\eta_{II,AHP}$, and solution circulation ratio (i.e. $f = \dot{m}_3/\dot{m}_7$) of the water/LiBr AHP (shown in Fig. 3(b)) are presented in Fig. 7(a–c). Waste heat between about 42 °C and 70 °C was amplified to useful process heat at temperatures ≥ 80 °C. The required driving heat inlet temperature is depicted in Fig. 7(d). The driving heat temperature is below 180 °C for a heat supply of 90 °C, and it is below 200 °C for a heat supply temperature of 100 °C.

For a heat supply of 90 °C, the thermal *COP* is about 1.582–1.718 and $\eta_{II,AHP}$ is 52.7– 64.6 % with a temperature lift up to 42 °C. For a heat supply of 100 °C, the thermal COP is about 1.562–1.651 and $\eta_{II,AHP}$ is 59.6–65.5 % with a lift up to 46 °C. It should be noted that a crystallization temperature margin of at least 5 °C is maintained at the exit to the SEV (stream 6, Fig. 3(b)) in this analysis, which is the most susceptible location for crystallization in the AHP.

2.2.3. Absorption heat transformers (AHTs)

Unlike Type I HP, the AHT functions without the need for driving heat source at high temperature as illustrated in Fig. 4(a). The performance map (maximum heat supply temperature [t_{16}^{max} in Fig. 4(b)], thermal COP_{AHT} and $\eta_{II,AHT}$) of a single-stage AHT are presented below by using the input operating and design parameters listed in Table 3.

The working range of water/LiBr AHT is also restricted by the water/LiBr solution characteristics [55,56]. In water/LiBr AHT, crystallization occurs at lower heat rejection and higher heat supply temperatures, and risk of crystallization is more at lesser SHX efficiency (i.e., higher SHX effectiveness value (e.g. 90 %) is used for AHT in contrast to AHP). The exit of the desorber (stream 1, Fig. 4(b)) is the most susceptible site from the viewpoint of crystallization since the highest LiBr concentration at

Table 3
Input modelling parameters of single-stage water/LiBr AHT (Fig. 4(b)).

Parameter and unit	Value/ Range
Heat source inlet temperature, t_{11}/t_{13} (°C)	70–100
Heat rejection medium inlet temperature, t_{17} (°C)	20–40
Heat source temperature gliding, ΔT_{glide}^{hs} (°C)	10
Heat rejection medium temperature gliding, ΔT_{glide}^{hr} (°C)	5
Approach temperature difference for ABS, CON, DES, and EVA, ΔT_{u}^{app} (°C)	5
Solution heat exchanger (SHX) effectiveness, ε_{shx} (%) [43]	90
Solution and refrigerant pump efficiencies, η_{sp} and η_{rp} (%)	70

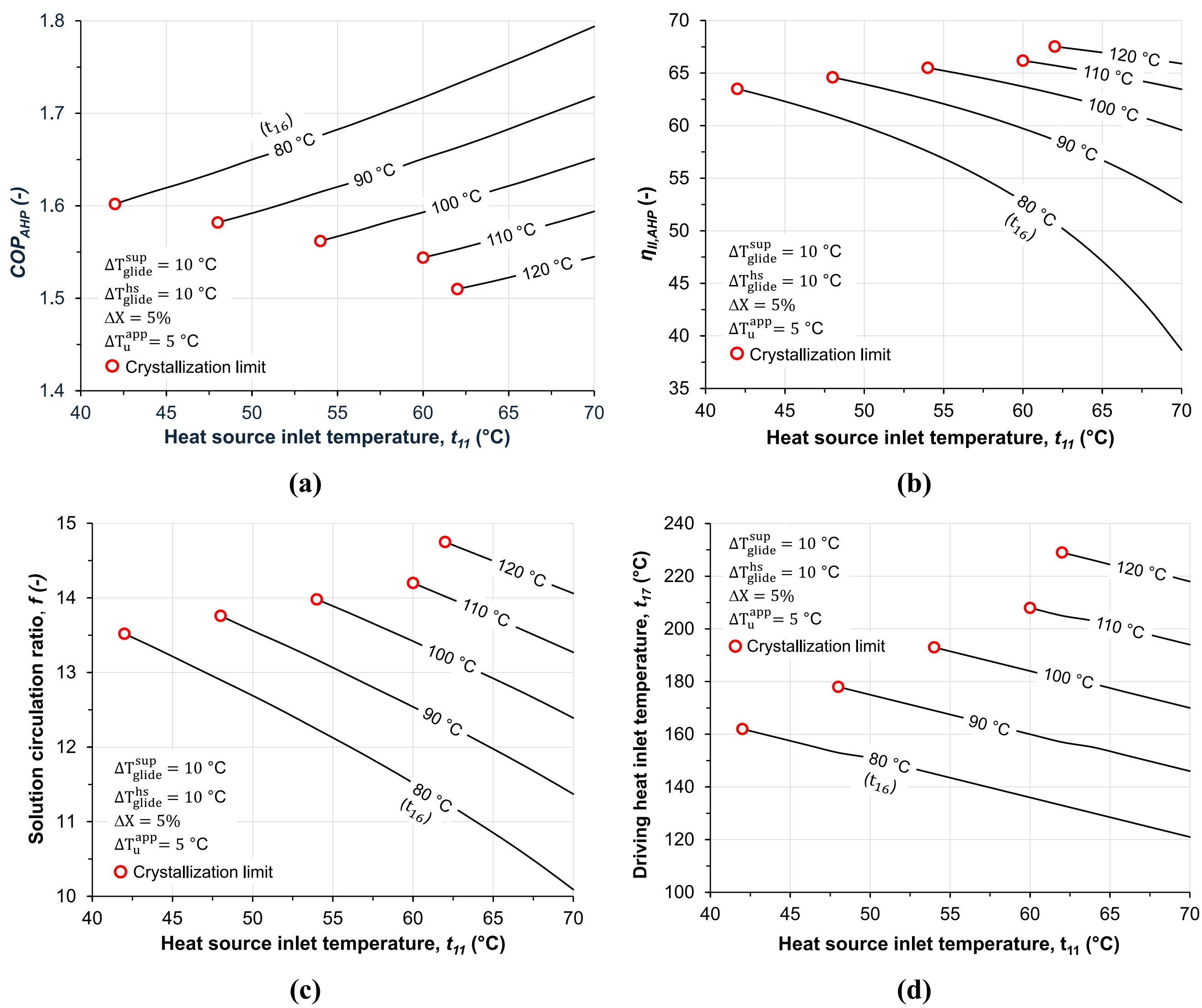

Fig. 7. Effect of heat source inlet temperature (t_{11}) at several heat supply temperatures (t_{16}) on **(a)** thermal COP_{AHP}, **(b)** $\eta_{II,AHP}$ **(c)** solution circulation ratio, and **(d)** driving heat inlet temperature (t_{17}) of single-effect water/LiBr AHP (Fig. 3(b)).

lowest temperature occur at this place of the AHT. Moreover, there is also a possibility of crystallization at the inlet of desorber (stream 6, Fig. 4(b)) due to the vaporization caused by water/LiBr solution expansion through the SEV particularly at higher absorber temperatures [56].

In Fig. 8(a), the maximum heat supply temperature (t_{16}^{max}, Fig. 4(b)) of single-stage water/LiBr AHT is illustrated as a function of heat source and heat rejection temperatures. This maximum heat supply temperature is obtained by setting a reasonable minimum temperature difference with the maximum temperature inside the absorber (i.e. $t_{16}^{max} = t_{abs}^{max} - \Delta T_{abs}^{min}$, $\Delta T_{abs}^{min} = 5\ ^\circ C$). The highest temperature in absorber (t_{abs}^{max}) is estimated/calculated using adiabatic absorption process model [43]. The corresponding $\eta_{II,AHT}$ of the single-stage water/LiBr AHT at the t_{16}^{max} is depicted in Fig. 8(b). The $\eta_{II,AHT}$ is between 51.5 % and 73.9 % with a maximum heat delivery temperature in the range of 80– 153 °C. The thermal COP is maintained at about 0.498–0.507 with temperature lift up to 53 °C. The crystallization temperature margin at the desorber outlet is higher than 5 °C in all performance simulations carried out in this study.

Using advanced AHT cycle configurations, higher COP or temperature lift can be achieved with various degrees of system complexity [57–59]. In comparison to single-stage AHT, a high-temperature lift can be achieved using an increased number of stages; however, the quantity of waste heat recovery diminishes (COP reduces). The performance of different types of AHT cycle configurations is depicted in Fig. 9 as a function of internal gross temperature lift (GTL), which is defined as $GTL = T_{abs} - T_{eva}$.

For example, double AHT [60–63], two-stage AHT [64], and triple AHT [65,66] cycle configurations can be used to increase the lift above 30–50 °C which is a typical value of single-stage water/LiBr AHT. To increase heat recovery, double-effect AHT can be used but limited lift is attained [67,68].

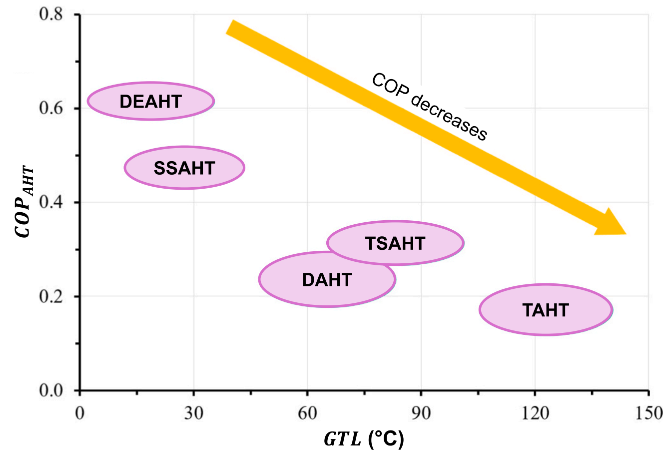

Fig. 9. Heating thermal COP (COP_{AHT}) vs gross temperature lift (GTL) for different types of water/LiBr absorption heat transformer (AHT) cycles. Note: DAHT = double AHT. DEAHT = double-effect AHT. SSAHT = single-stage (single-effect) AHT. TAHT = triple AHT. TSAHT = two-stage AHT.

3. Commercial absorption-based industrial heat pumps

3.1. Absorption-compression heat pumps (ACHPs)

The ACHP using ammonia/water mixture as a working fluid has been developed and commercialized by Hybrid Energy AS (Norway) since 2004 and recently acquired by Sabroe-Johnson Controls [69]. The main features of this HP technology (Sabroe hybrid HP) are a heat supply of up to 120 °C, waste heat recovery of up to 90 °C, use of standard ammonia HP components, operation at a lower system pressure (< 25 bar) than ammonia VCHPs at the same heat delivery temperature. The HP can also adapt to the heat source and heat supply streams temperature gliding.

The Sabroe hybrid HP products manufactured by Johnson Controls include the families HyePAC (single-stage HPs) and HyePAC-D (two-stage HPs). The heating capacity of these HPs is in the range of 500 to 2300 kW by using single and twin Sabroe reciprocating compressors. These HPs achieved electrical heating COPs of 3.4 –7.3 for a temperature lift of 60–25 °C [69].

The Calora heat pump (TRL 8 – 9), developed by AGO GmbH Energie + Anlagen (Germany), is based on the ammonia/water ACHP cycle, offering heating capacities from 0.7 MW to 10 MW [70,71]. Designed for high-temperature applications with heat supply temperatures between 50 °C and 160 °C and temperature lifts up to 110 °C [71]. Its modular design includes up to three compression stages, each with parallel piston or screw compressors, and operates efficiently with various heat sources, including ambient air, cooling water, river water, and exhaust air, at temperatures ranging from − 10 °C to 90 °C. The HP utilizes various types of heat sinks such as hot water, thermal oil, or steam, reaching a maximum steam pressure of 3.0 bar (140 °C). The use of frequency-controlled compressors and solution pumps enables

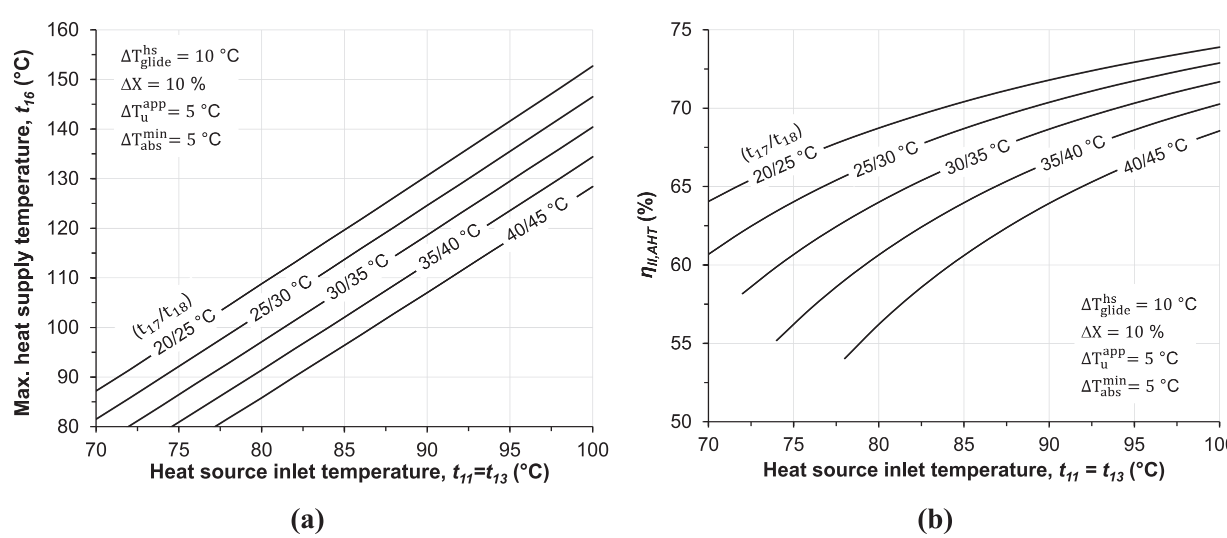

Fig. 8. Performance of single-stage water/LiBr absorption heat transformer. **(a)** Maximum heat delivery temperature; **(b)** $\eta_{II,AHP}$ at maximum heat delivery temperature.

efficient part-load operation down to 30 % of nominal capacity. The heat pump has achieved electrical heating COP of 5.1 at heat source and heat supply inlet/outlet temperatures of 85/70 °C and 90/130 °C, respectively [71].

3.2. Absorption heat pumps (Type i HPs)

Type I HPs that can supply heat at 80 °C at least are available on the market with a range of capacities from some of the well-established manufacturers of absorption technology (Table 4). These manufacturers produce water/LiBr Type I AHPs that deliver heat up to 100 °C.

Broad Air-Conditioning (China) [72] builds direct-fired (BDZ model) and indirectly driven (BDH-hot water-driven and BDS-steam-driven) single-effect water/LiBr AHPs with heat supply temperatures between 40 °C and 95 °C. They have been designed for low-temperature waste heat recovery with heating capacity ranges from 282 to 56,489 kW with a typical rated heating COP of 1.7. These AHPs use low-temperature waste heat sources from, for example, power plant cooling towers and industrial processes at a temperature between 15 °C and 50 °C.

The French manufacturer CNIM Group offers single-effect water/LiBr AHPs with a maximum heat supply temperature of 100 °C at a heating COP of about 1.7 [73]. Different types of low-temperature heat sources can be used in this heat pump including waste heat (30–50 °C), turbine exhaust stream, and renewable heat sources such as geothermal water (30–50 °C). This manufacturer also supplies tailor-made AHPs with a heating capacity of up to 20 MW using both direct- and indirect-fired technologies (hot water, steam [3–10 bar], gas, and hot oil). Ebara Refrigeration Equipment & Systems Co. Ltd (China/Japan) has been marketing single-effect water/LiBr AHPs since 1971 [74]. The Ebara RHP product line has wide applications with a typical temperature lift of 40 °C and a heating thermal COP of 1.7. This HP delivers heat at a temperature between 40 °C and 100 °C.

The YORK® YHAP-C product line of Johnson Controls-Hitachi Air Conditioning (Japan) single-effect water/LiBr AHP includes an indirect-fired machine (using exhaust gas, steam, hot water) and a direct-fired machine [75]. The YHAP-C AHP has a heating capacity between 900 kW and 40,000 kW (including custom-made products) with a maximum heat supply temperature of 95 °C and a heating thermal COP as high as 1.7. LG Electronics (South Korea) designed and developed single-effect water/LiBr AHPs (WCPX model) with a heating capacity greater than 300 kW [76]. The heating capacity of the steam-driven WCPX model is between 349 and 30,218 kW and the direct-fired WCPX model is between 349 and 9,530 kW. The WCPX model of LG Electronics can supply hot water at a temperature as high as 90 °C with a COP in the range of

Table 4
Commercially available water/LiBr absorption heat pumps (Type I HPs, AHPs) from leading absorption technology manufacturers (for heat delivery temperature ≥ 80 °C).

Manufacturer	Technology	Driving Energy Source	Heat Source	Delivered Heat	Heating Capacity (kW)	COP[a] (−)
Broad Air-Conditioning [72]	Single-effect (Direct/ Indirect-fired) Models: BDZ (Direct-fired); BDH (hot water-driven); and BDS (Steam-driven)	Hot water Steam Exhaust gasFuels: NG, biogas, diesel, etc.	Waste heat from power plant cooling tower (15–30 °C) Industrial waste heat (up to 50 °C)	Hot water up to 95 °C (40–95 °C)	282–14122 (BDZ) 557–27829 (BDH)282–56489 (BDS)	1.7[b]
CNIM [73]	Single-effect (Direct/ Indirect-fired)Tailored made heat pumps	Steam (3–10 bar)	Waste heat[c] (30–50 °C) Steam turbine exhaust (8–10 kPa)Geothermal water (30–50 °C)	Hot water up to 100 °C	200–20000	1.7
Ebara Refrigeration Equipment & Systems Co., Ltd. [74]	Single-effect (Direct/ Indirect-fired) Models: RHP Steam/hot water/exhaust gas-driven AHP;RHP Direct-fired AHP	Hot water (> 90 °C) Steam (1–8 bar)Exhaust gas (> 250 °C)Fuel: NG, City gas, Light Oil, etc.	Waste heat (exhaust steam or water at temperatures between 10–70 °C)	Hot water up to 100 °C (> 40 °C)	300–60000	1.7
Johnson Controls-Hitachi Air Conditioning [75]	Single-effect (Direct/ Indirect-fired)Model: YORK® YHAP-C	Hot water Exhaust gasSteam (3–9 bar)Fuel: N/R	Waste heat (typically, between 30 and 50 °C)	Hot water up to 95 °C (60–95 °C)	900–40000	1.7
LG Electronics [76]	Single-effect (Direct/ Indirect-fired)Model: WCPX	Hot water Steam (at 8 bar)Fuel: Gas	Waste heat source at 46 °C (inlet/outlet 46/40 °C)	Hot water up to 90 °C (55–90 °C)	349–30218 (steam-driven) 349–9530 (direct fired)	1.65–1.8
Shuangliang Eco-Energy Systems Co., Ltd. [78]	Single-effect (Indirect-fired)	Hot waterSteam (≤ 8 bar)Flue gas	Waste heat (hot water, gas or liquid at temperature 20–70 °C) (20–50 °C)	Hot water up to 100 °C (55–100 °C)	<70,000[d] (1000–35000)	1.65–1.8
Thermax Ltd. [77]	Single-effect (Direct/ Indirect-fired)	Hot water (130–180 °C)Exhaust gas (275–600 °C) Dry saturated steam (2–11 bar)Fuel: Gas, Oil, Propane, and LPG	Cooling tower water,process condensate/hot water, geothermal water (30–60 °C)	Hot water up to 90 °C (35–90 °C)	250–40000	1.65–1.75
World Energy Co., Ltd. [79]	Single-effect (Direct/ Indirect-fired) Direct-fired model: HPDSteam-driven model: HPS	Steam (pressure N/R) Fuel: LNG, LPG, and Oil(Kerosene, Diesel)	Waste heat (water at inlet/ outlet temperatures of 30/ 20 °C)	Hot water at inlet/ outlet temperatures of 20/80 °C	670–4687	1.65

Note: [a] thermal heating COP. [b] Includes pump power consumption. [c] Coming from a scrubber for flue gas cleaning. [d] Single unit can be more than 70 MW. LNG = Liquefied natural gas. LPG = Liquefied petroleum gas. NG = natural gas.
N/R = not reported.

1.65–1.80. Moreover, the Thermax (India) single-effect water/LiBr AHP also supplies heat at a maximum temperature of 90 °C using different types of driving heat in their indirect-fired AHP models [77]. These HPs use waste heat and renewable heat between 30 and 60 °C as a heat source and have a COP between 1.65 and 1.75. The Chinese manufacturer Shuangliang Eco-Energy Systems also offers indirect-fired single-effect water/LiBr AHPs with a maximum heat supply temperature of 100 °C and a COP as high as 1.8 [78]. World Energy (South Korea) provides direct-fired and steam-driven single-effect water/LiBr AHPs (HPD and HPS models, respectively) for hot water supply at 80 °C with a COP of 1.65 [79].

Besides, some of the manufacturers listed in Table 4 (e.g., CNIM, Ebara, and Johnson Controls-Hitachi Air Conditioning) produce double-effect water/LiBr AHPs with a thermal heating COP of 2.3–2.4. However, the heat supply temperature is lower than 80 °C and the temperature lift below the values achieved by the single-effect water/LiBr AHPs.

3.3. Absorption heat transformers (Type II HPs)

The AHTs on the market are based on single-stage water/LiBr absorption technology. The AHT product lines of the main absorption technology manufacturers are listed in Table 5.

Ebara [80] offers single-stage water/LiBr AHT that can supply hot water or steam (produced separately) at a maximum supply temperature of 175 °C. This heat pump operates at a heating COP of 0.33–0.48 with a typical temperature lift of 40 °C using a waste heat source above 80 °C. The AHT has a steam production capacity in the range of 0.3 to 15 t/h (tonnage per hour) at a supply pressure of 8 bar (i.e., 169–8460 kW of heating capacity). The CNIM also provides custom-made AHT for the valorisation of industrial waste heat in its absorption technology product lines. However, there are limited technical details of the machine on the company's website [81].

The single-stage water/LiBr AHT developed by Jonson Controls-Hitachi Air Conditioning supplies hot water (or steam) at 70–140 °C for various applications using waste heat below 100 °C [82]. The company offers AHTs with a heating capacity as low as 150 kW operating at a typical heating thermal COP of 0.45. LG Electronics also offers single-stage water/LiBr AHT with a heat supply temperature as high as 120 °C [83]. Thermax single-stage water/LiBr AHT technology uses different types of heat sources that can be used individually or in combination to deliver hot water up to 185 °C [84,85]. It covers heating capacities from 500 to 15,000 kW at a typical temperature lift of 50 °C [84,85]. The AHTs of Shuangliang Eco-Energy also use a range of heat source types (≥ 60 °C) to deliver hot water or steam at a heating COP of 0.46 [78]. The AHT from the World Energy achieves a heating COP of 0.48 at a heat supply temperature of 133 °C using a heat source and cooling water inlet temperatures of 88 °C and 26 °C, respectively [86]. The single-stage water/LiBr AHT, developed by BS Nova Apparatebau GmbH (Germany), is designed to upgrade heat in the range of 110–120 °C [87,88].

In summary, the commercially available Type I HP (AHP) and Type II HP (AHT) machines for industrial applications (≥ 80 °C) are limited to a single-stage water/LiBr absorption technology. Moreover, ammonia/water-based Type I and Type II HP products are scarce in the market for high-temperature heat pumping applications (>80 °C). Except, the single-stage ammonia/water AHT (AGO Calforma heat transformer) from AGO GmbH Energie + Anlagen (Germany), with a heating capacity in the range of 0.4–1.5 MW, that supplies hot water in the range of 60–110 °C using waste heat between 45 °C and 70 °C [89]. The AGO Calforma heat transformer operates at a thermal heating COP of 0.35–0.50.

4. Global deployment of absorption-based industrial heat pumps

The potential of ACHP, AHP, and AHT to upgrade industrial waste heat to a useful temperature level (≥80 °C) has been demonstrated in several industrial applications, and selected representative cases for each technology are discussed in this section.

4.1. Absorption-compression heat pumps (ACHPs)

The ACHPs developed by Hybrid Energy AS (now Sabroe Johnson Controls [90]) have been installed in various industrial sectors including dairies, abattoirs, fish feed producers, biogas production plants, and process industries. The company has commissioned more than 20 ACHP systems to date, which have proved to operate reliably for over 600,000 h [91]. Some of the main industrial deployments of this technology are described below [91–93].

The TINE SA dairy processing plant in Bergen (Norway)

Table 5
Commercially available single-stage water/LiBr absorption heat transformers (Type II HPs, AHTs) from leading absorption technology manufacturers.

Manufacturer	Heat Source	Heat Rejection	Delivered Heat	Heating Capacity (kW)	COP[a] (–)
Ebara Refrigeration Equipment & Systems Co., Ltd. [80]	Waste hot water; exhaust steam; and steam (>80 °C)	Cooling water(temperature: N/R)	Hot water or steam[b] up to 175 °C	169–8460	0.33–0.48
Johnson Controls-Hitachi Air Conditioning [82]	Waste heat (<100 °C) from engine jacket water; industrial processes; and distillation heat	Cooling water; underground water; recovery cooling water (inlet 24–32 °C)	Hot water or steam[b] up to 140 °C (70–140 °C)	150 3002475	0.45
LG Electronics [83]	Hot water at 70 °C	Cooling water at 12 °C	Hot water up to 120 °C	> 300	0.45
Shuangliang Eco-Energy Systems Co., Ltd. [78]	Waste hot water (≥ 60 °C) Exhaust steam; gas; and liquid (≥ 90 °C)	Cooling water (inlet 18–34 °C)	Hot water (130–169 °C) Steam[b] (1–6 bar)	< 8000[c] (1000–9300)	0.460.44–0.48
Thermax Ltd. [84,85]	Hot water/process condensate; geothermal water; and steam condensate from steam turbine (80–150 °C)	N/R	Hot water (110–185 °C) Dry saturated steam[b] (2–12 bar)	500–15000	0.40–0.47
World Energy Co., Ltd. [86]	Hot or drain water (at 88 °C)	Cooling water (inlet/outlet 26/32 °C)	Hot water (inlet/outlet 127/133 °C)	349–2442	0.48
BS Nova Apparatebau GmbH[d] [87,88]	Industrial waste heat (inlet/outlet 85/75 °C)	Cooling water (inlet/outlet 15/25 °C)	Hot water (inlet/outlet 111/116 °C)	448	0.48

Note: [a] thermal heating COP. [b] steam generated using separate flash tank. [c] single unit can be up to 8000 kW. [d] AHT technology provider of recent EU R&D projects [87,88]. N/R = not reported.

implemented the ammonia/water ACHP (GreenPAC) to deliver hot water at 95 °C for CIP (clean-in-place), pasteurization and other high-temperature heat requirements in the plant [93]. The GreenPAC heat pumps (ACHP), R717 VCHPs, and R717 chillers were used in an integrated energy recovery project for the use of heat pumps to deliver the heating and cooling needs of the plant (Fig. 10). The VCHPs amplify the heat rejected by the chillers (at 40/20 °C inlet/outlet) to the heat source stream temperature level (at 67/60 °C inlet/outlet) used in the GreenPAC (single-stage ACHP). The maximum heating capacity of the GreenPAC was 940 kW with an electrical heating COP of 5.4 and a temperature lift of 28 °C.

In 2017, a single-stage ACHP with a heating capacity of 2 MW was commissioned in Borregaard ASA's bio-refinery process plant in Sarpsborg (Norway) to pre-heat the feed water of the plant's steam boiler. The waste heat source (at 73 °C inlet) is amplified by the ACHP to the feed hot water at 95 °C at an electrical heating COP of 6.1 (at 22 °C lift). Therefore, the plant significantly benefited because the annual energy consumption reduced by 60 GWh.

In 2016, the two-stage ACHP with a heating capacity of 800 kW was installed in a wastewater treatment plant of the biogas production company Frevar KF in Norway to supply hot water at 95 °C. Using the central heating system of the plant, the hot water produced is used in several applications including preheating feed sludge, heating buildings, and other processes in biogas production. The heat pump has an electrical heating COP of 2.4 with a large temperature lift of 75 °C. Moreover, in 2019, the wastewater treatment plant (BEVA in Norway) started installing its second 800 kW ACHP (a two-stage heat pump) to supply heat to the rotting tanks producing biogas by recovering heat from the fermented sludge.

In 2015, the DH company Løgumkloster Fjernvarme (Denmark) installed a two-stage ACHP (Fig. 11) with a heating capacity of 1.3 MW in its South Jutland facility to provide hot water at 100 °C. The waste heat (at 35/17 °C inlet/outlet) was recovered from the company's CSP (concentrated solar power) plant.

The heat pump operates at an electrical heating COP of 4.3 with a large lift of 65 °C. The ACHP also supplies cooling to other heat production processes within the DH facility including the solar collector field. The use of ACHP reduces the consumption of natural gas by about 0.793 Mm^3/year; subsequently, it has led to an annual reduction of 528 and 1.8 metric tons of CO_2 and NOx, respectively.

In 2013, a two-stage ACHP with a heating capacity of 1405 kW was installed for drying applications at the Skretting factory in Stokmarknes (Norway). The heat pump recovers heat from exhaust air (at inlet/outlet of 42/28 °C) to supply heat at 85 °C. The supplied heat is used to preheat drying air and other processes. It operates at an electrical heating COP of 5.5 with a temperature lift of 43 °C and it reduces the overall energy consumption of the factory by 20 %. Using a single-stage ACHP with a heating capacity of 1.2 MW installed in 2012, the Arla Arinco dry milk plant (Denmark) saved 4.6 GWh of energy yearly with a shorter payback period (about 20 months). The reduction in CO_2 eq. emission was 1,400 metric tons per year. This heat pump delivered heat at 85 °C (from 55 °C) for drying applications using waste heat (at inlet/outlet of 45/22 °C) recovered from the evaporation process used to heat up process air. The heat pump operates at an electrical heating COP of 4.5 with a lift of 40 °C.

4.2. *Absorption heat pump (Type i HP)*

A single-effect water/LiBr AHP manufactured by CNIM and with a heating capacity of about 7 MW has been installed at the Schweighofer Fibre GmbH (Austria), now AustroCel Hallein GmbH, (Fig. 12) [94,95]. It is used to recover waste heat from the flue gas condensation of the biogas plant and supplies heat at about 90 °C with thermal heating *COP* of about 1.8. The heat pump is driven by steam at 165 °C obtained from the biomass cogeneration plant. A complete heat recovery system based on the CNIM single-effect water/LiBr AHP has been implemented at a brick manufacturing plant (France) to recover waste heat of about 500 kW and to supply the plant with 1.2 MW of heat with a heating thermal *COP* about 1.71. The CNIM AHP has also been applied in district heating (DH) plants: for example, industrial waste heat recovery in Switzerland (240 kW in pharmaceutical industry).

Using a Broad single-effect water/LiBr AHP [72], two thermal power plants in South Korea recover about 48 MW of heat rejected by condenser cooling water (15–30 °C) to produce hot water at 80 °C for district heating applications. The driving heat ($\geq$ 5.1 bar, $\leq$ 180 °C) of this heat pump is obtained from a large-scale steam turbine. A Broad single-effect AHP is also used to recover about 24 MW of waste heat (30 °C) from a dyeing process mill (in South Korea eco-park) and deliver hot water at 83 °C for district heating applications. This heat pump is also used for district heating applications in Austria, where it recovers about 2.3 MW of heat from cooling water (40 °C) in a steelwork to produce hot water at 85 °C. In a paper factory in Thailand, low-temperature waste heat of 3.3 MW is recycled to produce hot water at 85 °C and preheat makeup water. Other industrial waste heat recovery applications include the recovery of 1.7 MW heat (about 50 °C) from brewery process to preheat boiler makeup water to 80 °C, and 1.2 MW

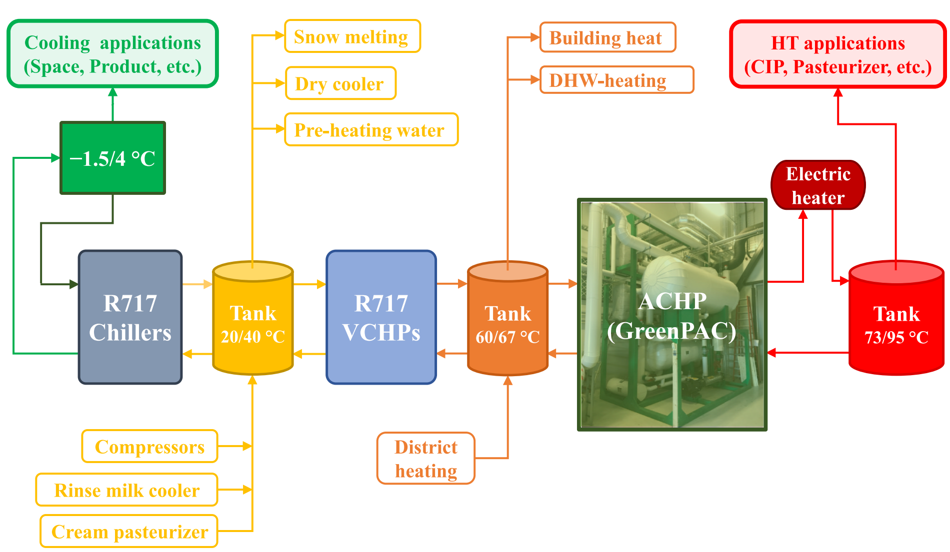

Fig. 10. Simplified flow diagram of integrated energy recovery system using heat pump technologies (single-stage R717 VCHPs and GreenPAC ACHP from Hybrid Energy AS) installed in a green-field dairy processing plant in Norway [93].

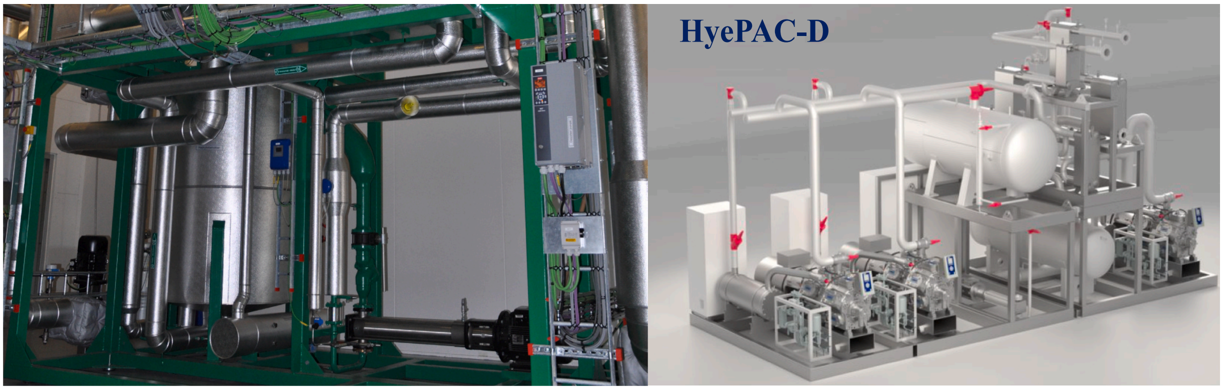

Fig. 11. Two-stage ammonia/water ACHP of 1.3 MW heating capacity installed in solar district heating facility in Denmark [91].

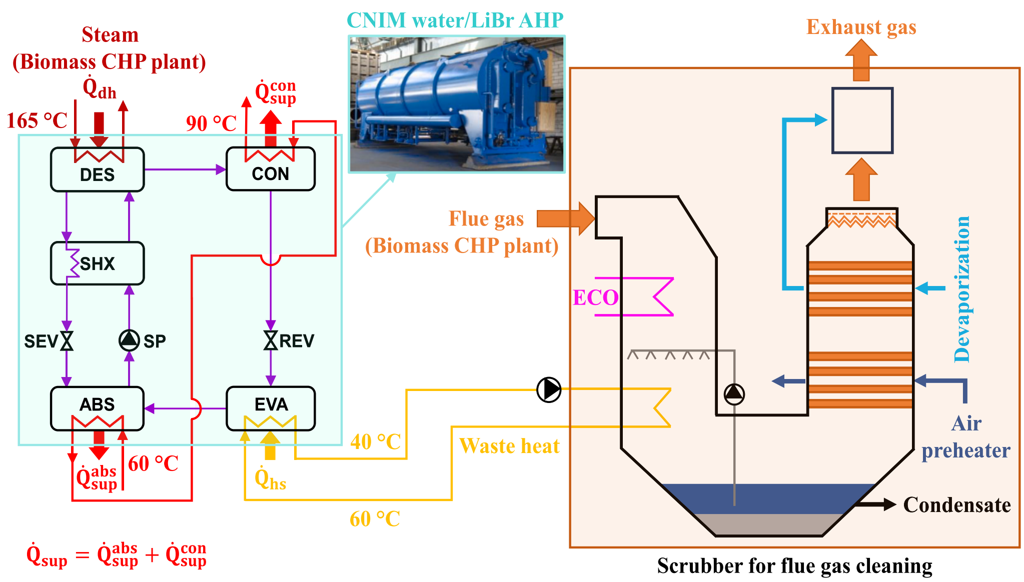

Fig. 12. Single-effect water/LiBr AHP (Type I heat pump) for waste heat recovery from flue gas condensation in a biomass CHP plant in Hallein (Austria) [94,95].

heat from cooling water (37 °C) of an air-conditioning system to produce hot water at 88 °C.

4.3. Absorption heat transformer (Type II HP)

In China, the first industrial-scale water/LiBr AHT was installed at the synthetic rubber plant of the Yanshan Petrochemical Corporation (Beijing) in 1999 [96]. The AHT is used to recover waste heat from a mixture of steam and organic vapour at 98 °C to heat hot water from 95 °C to 110 °C. The hot water produced is used as a heating source in the coagulator of the plant. The first plant used a 5 MW single-stage water/LiBr AHT (Fig. 13) and later expanded to incorporate two other

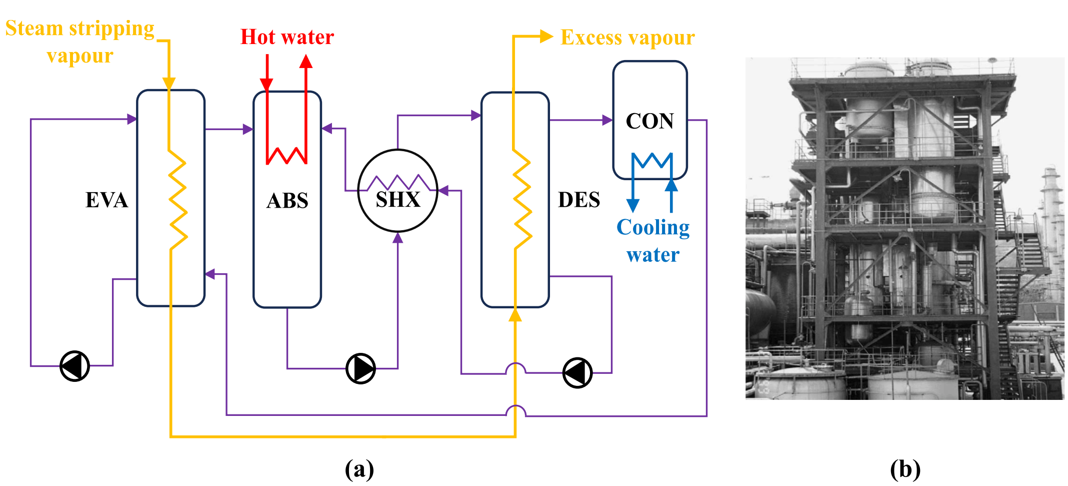

Fig. 13. Single-stage water/LiBr AHT (Type II heat pump) installed in China to recover waste heat from a synthetic rubber plant [96]. (a) AHT simplified flow diagram, (b) Installation of 5 MW AHT.

similar types of AHTs with a heating capacity of 7 MW, because of the success of the first AHT (i.e., the plant steam consumption reduced by 59 % and an estimated payback period of 2 years). The AHT operates at an average thermal COP of 0.47 using cooling water at an inlet temperature of 28–30 °C.

A single-stage water/LiBr AHT, from Thermax Ltd., has been installed and is operating in a poly film manufacturing plant for PV cells of the Asia Silicon Co. Ltd in China (Fig. 14) [97]. The heat rejected in the cooling process is used to produce 6.5 t/h of steam at 4 bar(g), which is used in the plant. The hot water produced by the single-stage AHT that circulates between the absorber (external loop) and the flash tank for stream generation is about 765 m^3/hr at inlet/outlet of 152/157 °C. Furthermore, Thermax single-stage water/LiBr AHTs have been implemented in food processing industries in Italy and Germany [98]. The AHTs are used to produce hot water at 135 °C for drying pasta at the Baronia Pasta Factory in Italy whereas hot water produced at 105 °C is used for cooking vegetables in the pre-cooked meal production factory in Renken (Germany). Waste heat from engine jacket water at 93 °C and 90 °C, respectively, are used as a heat source in both installations.

5. Research projects and new developments

This section mainly focuses on research activities and progress in ACHP and AHT systems since research projects and new developments related to AHPs are limited for heat supply at high temperature.

5.1. Absorption-compression heat pumps (ACHPs)

A prototype of ammonia/water ACHP with a 200 kW maximum heating capacity was built at the NTNU (Norway) as part of the High-EFFLab project [99]. The prototype, shown in Fig. 15(a), is designed to operate at a maximum pressure and temperature of 40 bar and 190 °C. An oil-free twin-screw compressor is used, which has three liquid injection ports (one at the beginning and two at the end from the rotor male and female sides, depicted in Fig. 15(b)). The weak ammonia/water solution is injected at these three locations of the compressor for lubrication, cooling, and sealing purposes. This heat pump performance studies, using numerical models developed based on the prototype's components and experimental campaigns, are going under the EU-funded ENOUGH project (10/2021–09/2025) [100–102]. However, the experimental results are yet limited due to the compressor malfunction [102]. Using the developed simulation model (for 150 kW heating capacity), it is shown the compressor's discharge temperature decreased from 276 °C to 160.3 °C and the heating COP increased from 2.14 to 2.85 due to the compressor intercooling using the weak ammonia/water solution [100,101]. The hot water supply temperature was at 105 °C when the system high and low pressures were 23.65 and 4 bar. Recently, an experimental optimization of this prototype with wet compression (using weak ammonia/water injection) has been carried out for industrial applications with large heat sink temperature glides [31,103]. The weak solution injection reduces compressor discharge temperature from 139 °C to 122 °C. These findings contribute to future advancements in the development of oil-free ammonia/water ACHP technology.

In the national R&D project by AGO (Germany) between 10/2018–06/2022, an ammonia/water ACHP with two-stage compression using intercooling by rich ammonia/water solution was built and tested [104]. It has two SHXs for internal heat recuperation and a rectification column to reduce desorber volumetric flow [104]. The project was aimed at the demonstration of the ACHP to supply heat (hot water or steam) between 100–160 °C by upgrading waste heat sources in the range of 60–100 °C. The prototype of the heat pump with a heating capacity of about 1 MW was installed and tested to supply hot water up to 150 °C for upgrading waste heat from the engine cooling of the CHP (combined heat and power) plant [105].

An ammonia/water single-stage ACHP test rig was designed and built at the Leibniz University (Germany) (Fig. 16(a)) [106]. The absorber/resorber and desorber/degasser are plate heat exchangers made of stainless steel (1.4401) at a design system high pressure of 26 bar. The ACHP system uses an oil-lubricated open screw compressor from BITZER Kíhlmaschinen GmbH (OSKA series type). The compressor was driven by an electric motor (92.4 % nominal efficiency), and it reached a maximum isentropic efficiency of 76.5 %. In this compressor, a synthetic oil lubricant based on α-olefins was used to avoid foam build-up in the heat exchangers, which reduces the rate of heat and mass transfer processes. In parallel, an oil separator was installed at the compressor outlet (Fig. 16(b)) to ensure that only ammonia/water vapour (<50 ppm of oil) flows into the absorber.

The single-stage ACHP was experimentally tested at heat source and heat supply stream inlet temperatures of 59 °C and 50 °C, respectively, with a heating capacity of 50 kW. Using the test rig built (Fig. 16), the influence of the weak (in ammonia) solution mass flow rate (between 0.21 kg/s and 0.31 kg/s) and absorption pressure (between 13.5 bar and 16.5 bar) on the heating capacity and electrical heating COP were investigated. The ACHP has achieved a maximum electrical heating COP of 2.5 while supplying over 40 kW of useful heat at a maximum of 43 °C internal gross temperature lift (defined as the difference between the logarithmic mean temperatures during the desorption and absorption processes).

An experimental setup of ammonia/water ACHP (Fig. 17) was built using a brazing-type plate heat exchanger for the absorber to improve the heat pump's performance [107]. The experimental study and heat pump cycle simulation with the parametric study were conducted to produce process heat (hot water) above 80 °C using an industrial waste

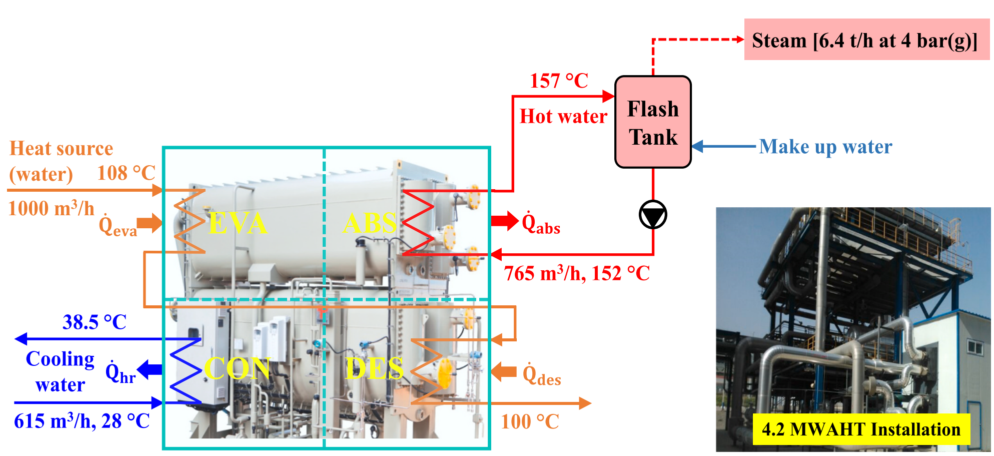

Fig. 14. Single-stage water/LiBr AHT (Type II heat pump) installed in a poly film manufacturing plant in China [97].

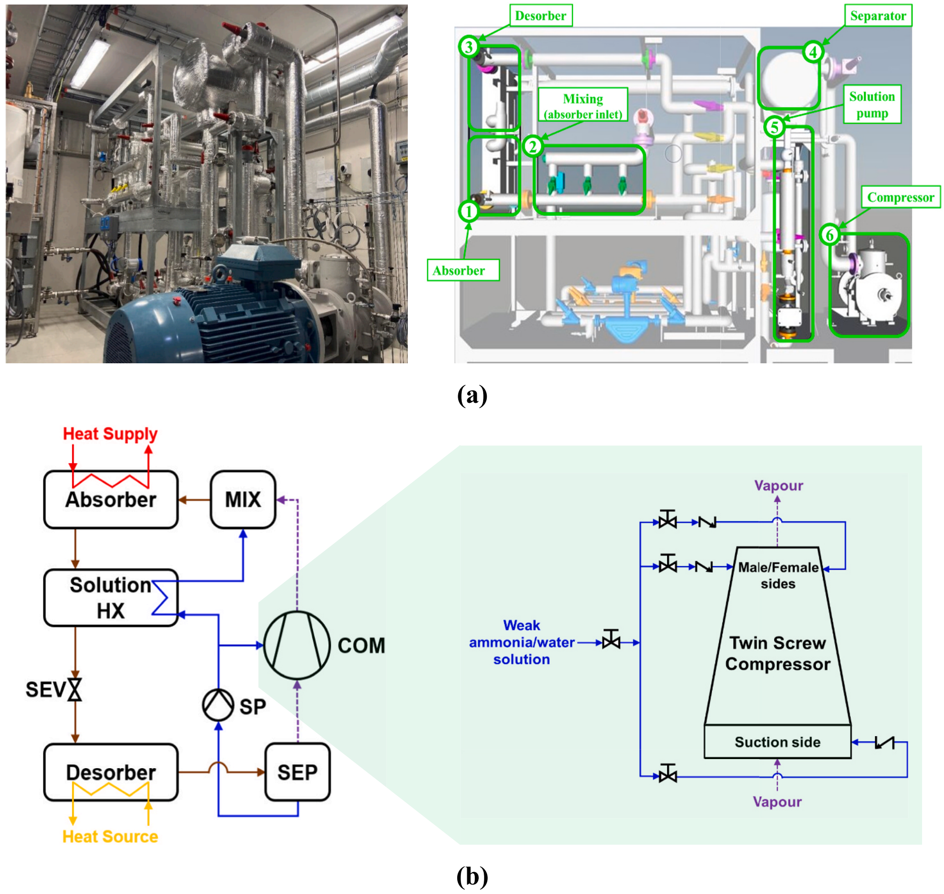

Fig. 15. An experimental prototype of an ammonia/water ACHP using an oil-free twin-screw compressor with liquid injection built at the Norwegian University of Science and Technology (Norway) [31,99]. (a) Prototype photo and 3D view and (b) ACHP cycle and compressor layouts.

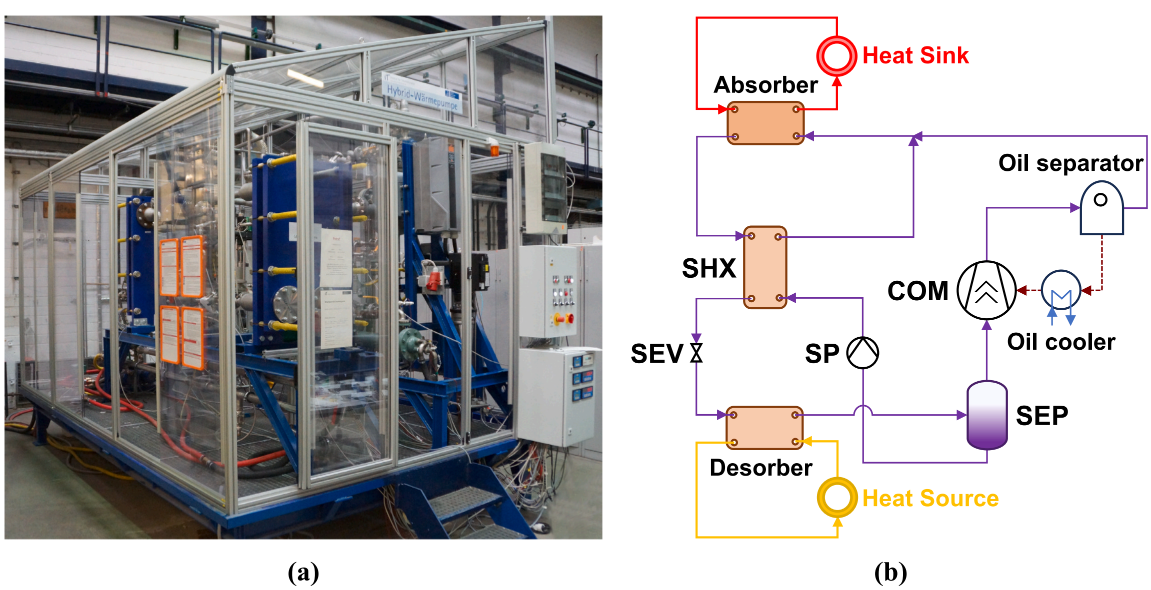

Fig. 16. A laboratory prototype of the ammonia/water ACHP developed at Leibniz University (Germany) [106]. (a) Photo of the prototype and (b) Simplified cycle layout of the experimental setup.

heat source of 50 °C. It is claimed that the concentration of weak solution should be kept at 0.40–0.45, the flow rate of the weak solution should be < 0.03 kg/s and the system high-pressure be > 17 bar to produce process heat > 80 °C.

In the HyPump project between 2012 and 2015, the Graz University of Technology (Austria) in collaboration with the Austrian Institute of Technology and Frigopol Kälteanlagen GmbH designed and developed a HTHP (Fig. 18(a)) based on the concept of ACHP (Fig. 18(b)) [108,109]. The developed ACHP uses an ammonia/$LiNO_3$ mixture as a working fluid that can deliver heat up to 110 °C. It was designed for decentralized

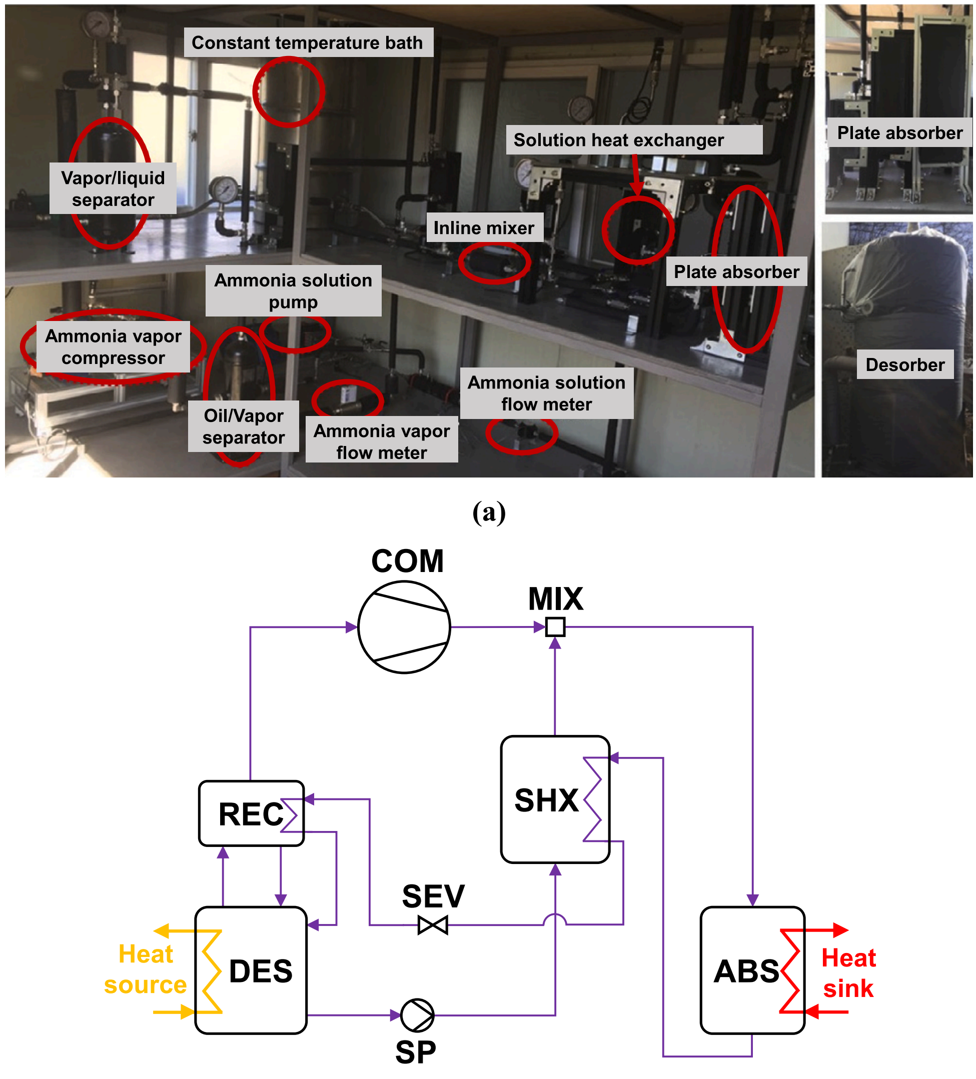

Fig. 17. An experimental setup of ammonia/water ACHP using a brazing-type plate heat exchanger absorber [107]. (a) Photo of the experimental setup and (b) Cycle layout of the experimental setup.

industrial waste heat recovery (30–60 °C) with a small-scale heating capacity (up to 50 kW). In this small-scale capacity range, cost-effective implementation of the ACHP was feasible due to the off-the-shelf components such as plate heat exchangers and the standard ammonia compressor.

The use of an ammonia/water-(or $LiNO_3$) based ACHP system for heat supply applications (>120 °C) is restricted due to the current technical challenges of system components, in particular, the compressor and the absorber. The compressor is the main limitation in achieving the desired high-temperature heat supply because of its high pressure and discharge temperature restrictions; and a comprehensive literature review on compressor technologies for HTHPs is reported [110]. The low density and specific heat capacity of the superheated ammonia vapour phase mean that the discharge temperature occurring during the compression process of ammonia is relatively high [111]; even in the ideal case, this temperature is far beyond the maximum temperature allowed for currently available standard compressor technologies. The compressor discharge temperature is even higher in the real compression process due to its irreversibility. This high discharge temperature leads to some technical problems, such as lubricant degradation and failure of compressor seals. Another critical component is the absorber because there is little knowledge and experience in the absorption process in this range of operating temperatures and pressures.

In parallel, the oil-free operation of the compressor is desirable to keep the system free of lubricant oil, especially for the heat and mass exchangers. Moreover, in the ammonia/water based ACHP system, the presence of water in the vapour stream makes oil separation more difficult and costly. So, only partial separation means that lubricant oil is present in other components (e.g. absorber), which affects the heat and mass transfer properties [112,113]. In this context, various solutions have been suggested to alleviate the challenges raised by the compression of ammonia vapour including multi-stage compression and liquid injection. However, these solutions have their corresponding disadvantages (high complexity and problems of evaporation, respectively). To date, reliable oil-free compressors with a liquid injection that can achieve the desired requirements are not readily available on the market.

Ahrens et al. [114] investigated compressor technologies on the market for the development of an ammonia/water ACHP test facility (shown in Fig. 15(a)) which can deliver heat at temperatures between 140 and 180 °C. To deliver the heat at this temperature with a high-temperature lift, the pressure ratio and discharge pressure need to be high; as a result, the compressor must withstand a discharge

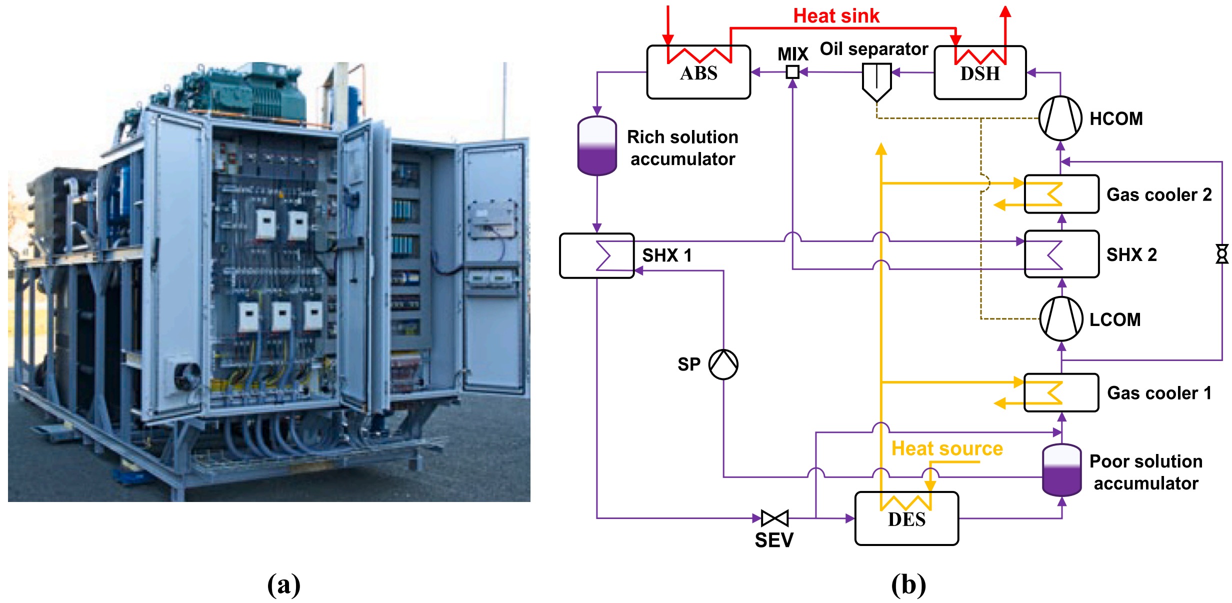

Fig. 18. A prototype of an ammonia/$LiNO_3$ ACHP developed in the HyPump project (Austria). (a) Prototype photo [108] and (b) Cycle layout [109].

temperature of at least 180 °C. Also, operation with normal lubricants should be possible only for discharge temperatures up to 180 °C [115] or 190 °C [116]. Thus, because they can provide high-pressure ratios and smaller swept volumes, positive displacement compressors (e.g., piston and screw compressors) have mostly been preferred to dynamic compressors.

Another promising approach to responding to the challenges of the dry compression process in the ACHP system is to use a wet compression of the biphasic working fluid stream (Fig. 19). This approach has several possible benefits: the compressor is lubricated by the working fluid so the heat pump functions without a lubricating oil; the compression process can be carried out in the two-phase region which avoids the superheating caused by irreversibility losses; the discharge temperatures remain low even at high compression ratios, and the heat pump COP can be increased (e.g., >15 % [117]) by wet compression.

The possibility of wet (two-phase) compression based on ammonia/water mixtures has been the focus of some research investigations at the Delft University of Technology (Netherlands) [117–123], in particular, the use of wet-compression HPs using ammonia/water mixtures and oil-free screw compressors.

Recently, a rotary vane compressor has been developed by Tocircle Industries AS (Norway) that can be used in ammonia/water heat pumps with wet compression of the working fluid [20,124]. The compressor operates without oil lubrication in the compression chambers since it is controlled using bearing technology mounted in the centre of the machine. The internal lubrication is achieved through liquid injection into the internal bearings of the compressor whereas the external bearings are lubricated with circulating oil in a closed separate system.

5.2. *Absorption heat transformer (Type II HP)*

In the European project Indus3Es (10/2015–04/2020), a single-stage water/LiBr AHT (Fig. 20) was developed to upgrade industrial surplus heat available at low-temperature (< 130 °C) [125]. The final aim of the project was to design and develop an absorption machine with a revalorization capacity of 200 kW at a gross temperature lift of about 40 °C

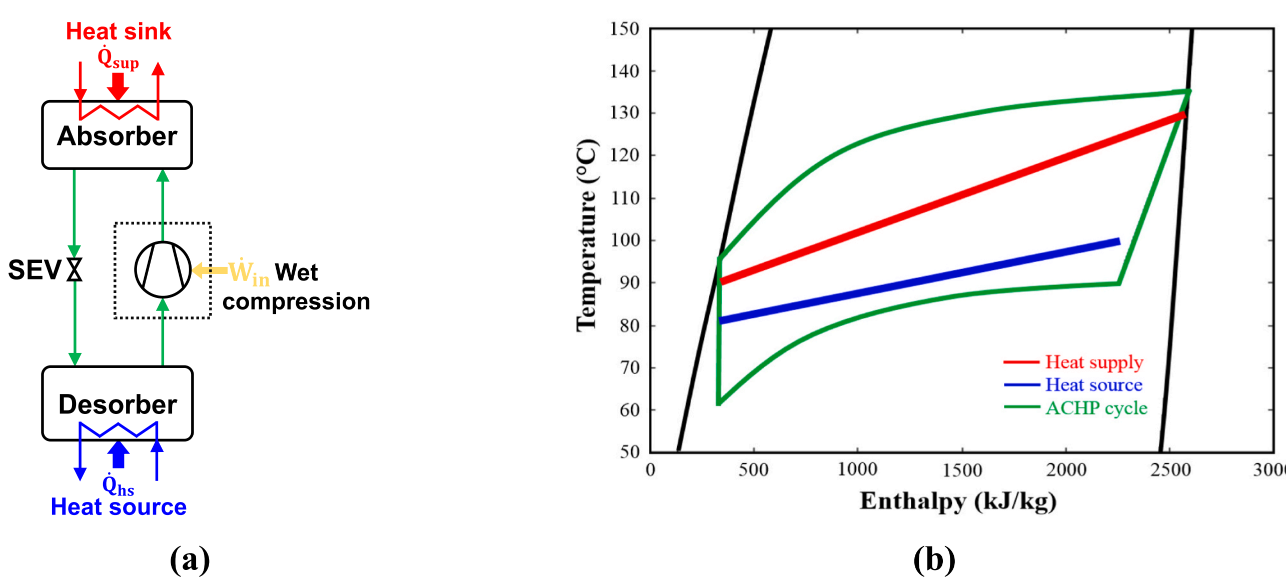

Fig. 19. Concept of the ACHP with wet (two-phase) compression. (a) cycle layout and (b) T-h diagram of the wet ACHP process for 16.6 wt% ammonia [117].

[126–130]. The AHT operates at a heating COP of about 0.45 using a heat source at 95 °C [125]. In this project, two innovative adiabatic absorption approaches were implemented (i.e., atomizing spray nozzles and a drip distribution system) to enhance the adiabatic absorption process [131]. Thereby, it increases the maximum attainable temperature within the absorber. Since the presence of non-condensable gases reduces the rate of the absorption process, the developed AHT was also equipped with a simple, efficient, and low-cost gas purging system (described for laboratory scale 10 kW AHT in Ref. [132]).

An experimental prototype of single-stage water/LiBr AHT for direct steam generation (Fig. 21) was built with two operating modes for waste heat source (hot water) flow connection between the evaporator and desorber [133]. The 12 kW prototype experimental study was carried out for steam supply at 120 °C. The measured heating COP was between 0.40 and 0.48 when the driving hot water source inlet temperature was between 80 °C and 95 °C (lift from 40 to 25 °C). Moreover, a 20 kW direct steam generation water/LiBr experimental prototype was designed and developed for heat supply up to 125 °C with ∼ 30 °C lift [134]. This prototype was built using vertical shell and tube heat exchangers for the main four components (i.e. ABS, CON, DES, and EVA) and a plate heat exchanger for the SHX. Further, different flow arrangements of the vertical absorber tubes were studied by the same researchers [135].

An experimental prototype of a single-stage ammonia/water AHT (Fig. 22) was designed and developed to use a heat source (hot water) input up to 12 kW at a temperature between 60–64 °C [136,137]. The condenser uses brine (40 % glycol) as its heat rejection medium with inlet temperatures between 8 °C and 16 °C. In this prototype, vertical falling-film type heat exchangers were used for the absorber and desorber whereas the condenser and evaporator were made of symmetrical flow boiling heat exchangers with vertical flow and shell and tube configuration. During the experimental test, the prototype operated at a heating COP in the range of 0.35–0.47 with a temperature lift up to 25 °C. Also, the maximum heating capacity of 4.5 kW was reached with an electrical power consumption of the pumps $<$ 0.1 kW.

A prototype of single-stage ammonia/water AHT was built for steam generation (<120 °C) using low-grade heat at 85 °C and its performance was experimentally investigated [138]. A maximum thermal COP and temperature lift of 0.33 and 35 °C, respectively, were reached within the considered experiment range. Based on the prototype experimental data, the estimated thermal COP of a 200 kW prototype was 0.36 when the heat supply temperature was 119.7 °C, which is similar to the simulation value of 0.38 [138].

Another working fluid used in the experimental study of a 5.5 kW single-stage AHT prototype was water/Ionic Liquid (EMIM OMs) and tested for driving heat source between 80–95 °C and heat supply 110–140 °C [139]. The obtained COP was 0.43 and 0.23 at *GTL* of 18.5 °C and 47 °C, respectively.

To achieve a larger temperature lift than the single-stage AHT, an experimental water/LiBr double AHT (DAHT) was developed and installed at the Universidad Nacional Autónoma de México (Fig. 23) [140]. The desorber and evaporator are stagnant pool boiling type heat exchangers which provide heat using electrical heaters (1 kW heating capacity) immersed in the corresponding water/LiBr solution and water. The remaining heat exchangers are coils inside shell configurations, the absorber and absorber-evaporator are of the vertical falling film type where oil and evaporating water passes through the tubes, respectively. The entire DAHT was built using type 316 stainless steel to avoid corrosion by the LiBr solution. The DAHT reached a maximum 74 °C gross temperature lift (with a range of 48–74 °C, defined as the difference between the absorber and evaporator exit temperatures), which is about 30 °C higher than a single-stage AHT (44 °C). The DAHT reached a maximum heating COP of 0.33 (between 0.12 – 0.33), which is calculated using measurements of the external heat carrier loop of the absorber (Mobil Therm oil) and heat loads of the desorber and evaporator from the electrical heaters.

A small-scale water/LiBr double-lift AHT prototype (Fig. 24) was built to generate steam at temperatures above 170 °C using hot water at about 80 °C [141,142]. The prototype used falling-film heat exchangers so that heat transfer coefficients are high and pressure drops insignificant. When surfactant additives were used, the heat and mass transfer rates were enhanced because of surface gradient-induced convection and mixing, also known as Marangoni convection [141].

This prototype has overcome the main technical challenges that limit the practical implementations of water/LiBr AHTs (e.g., crystallization, corrosion of standard heat exchanger materials, and air infiltration [98]) and has shown that they can be operated steadily, efficiently, and safely. Moreover, the prototype was used to optimize an industrial-scale heat pump and, finally, a heat transformer with a heating capacity of 200 kW was built to demonstrate its industrial-scale application [143]. The

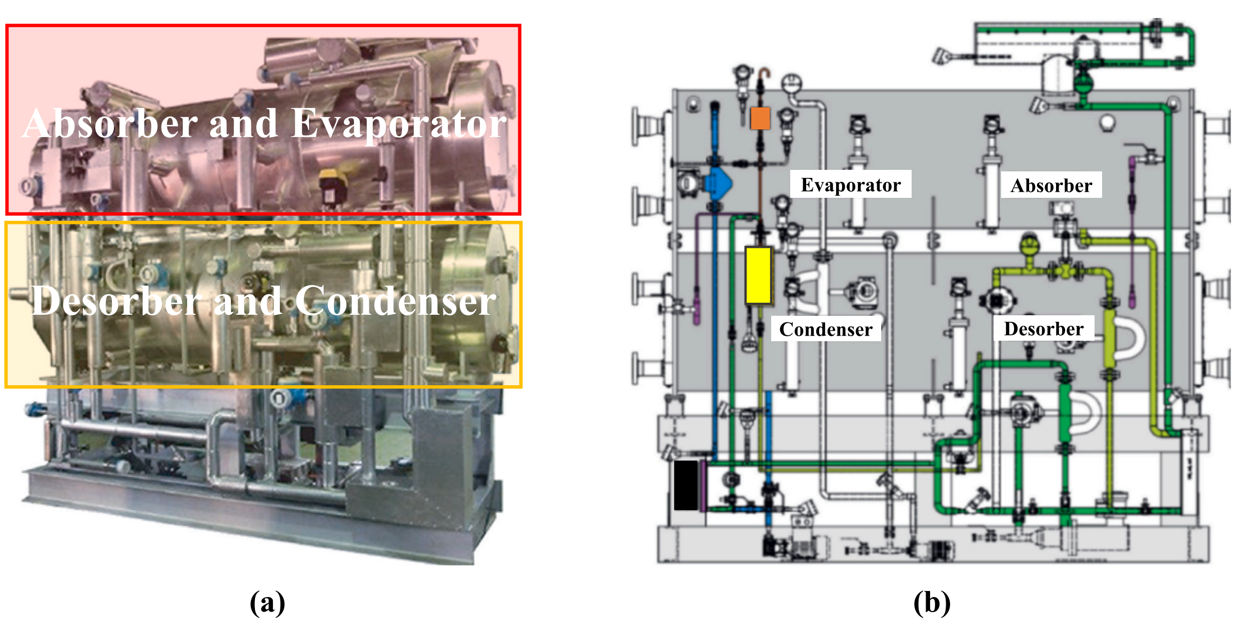

Fig. 20. Single-stage water/LiBr AHT (Type II heat pump) prototype developed in the Indus3Es project (EU countries) [125]. (a) AHT prototype internal view; and (b) AHT component layout.

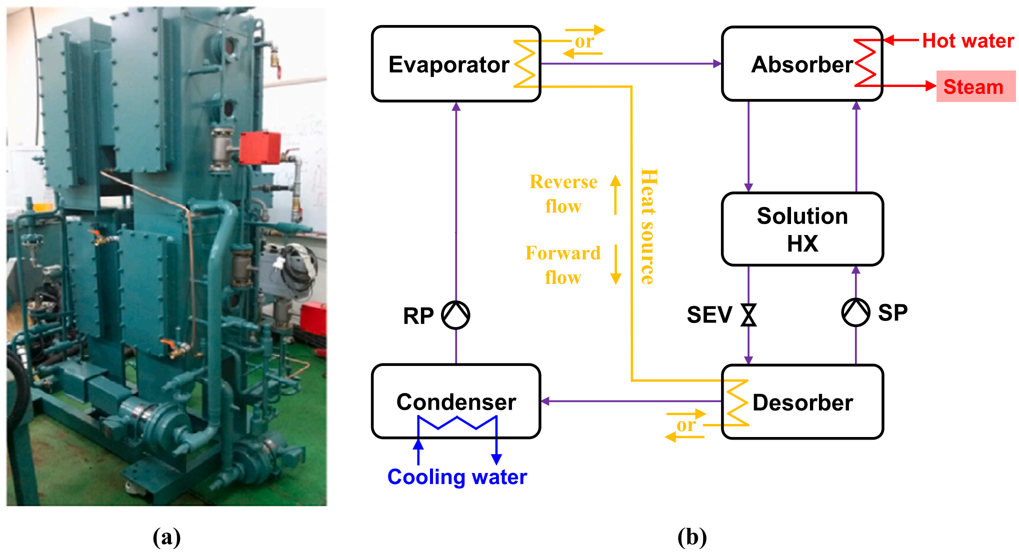

Fig. 21. Direct steam generation single-stage water/LiBr AHT (Type II heat pump) experimental prototype (Republic of Korea) [133]. (a) Photo of external view and (b) Cycle layout with two modes of waste heat source (hot water) connection.

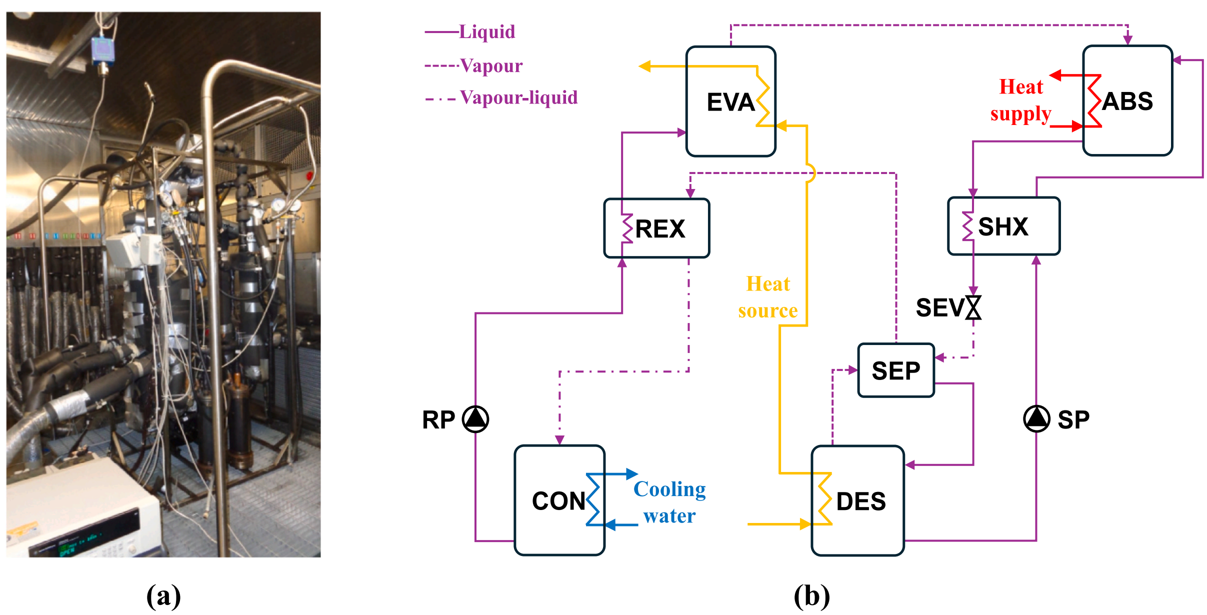

Fig. 22. A laboratory prototype of single-stage ammonia/water AHT (Type II HP) developed at the Politecnico di Milano (Italy) [136,137]. (a) Prototype experimental setup; (b) Cycle layout.

performance and operation of this double-lift AHT were experimentally studied at a hot water and a cooling water inlet temperature of 80–90 °C and 20–30 °C. The system reached a COP of > 0.3 (0.24–0.33) with a lift of 86 °C at a heat source inlet temperature of 84 °C.

An innovative ammonia/water AHT including a two-phase ejector is currently under development within the Horizon EU-funded ZIMBA project [144]. It is designed to upgrade and supply heat at 110 °C with a heating capacity of 15 kW, this AHT aims to reach a TRL of 4 [144]. The use of the two-phase ejector is aimed at enhancing system stability and extending its operational range, particularly under hot conditions, ensuring improved performance and reliability throughout varied operational scenarios.

6. Discussion

Ammonia/water ACHPs, water/LiBr AHPs, and water/LiBr AHTs are gaining interest for industrial waste heat recovery, including applications requiring heat supply above 80 °C. The Sabroe ACHP, for instance, operates with an electrical heating COP ranging from 3.4 to 7.3 and offers flexibility in adapting to varying heat source and sink temperature glides, making it highly flexible for integration with various industrial processes. AGO GmbH's Calora heat pump, designed for high-temperature applications, operates with heat source temperatures from − 10 °C to 90 °C, providing heat up to 160 °C and generate steam with maximum pressure of 3.0 bar (140 °C). Most commercially available AHPs and AHTs are based on single-stage water/LiBr absorption technology from global manufacturers such as Broad Air-Conditioning, CNIM, Ebara, Johnson Controls-Hitachi, LG, Shuangliang Eco-Energy Systems, Thermax, and World Energy. These heat pumps typically offer heating capacities of up to 70 MW (AHPs) and 15 MW (AHTs), with thermal COPs between 1.65 and 1.8 for AHPs and 0.33–0.48 for AHTs. In contrast, ammonia/water-based AHTs remain scarce, with limited

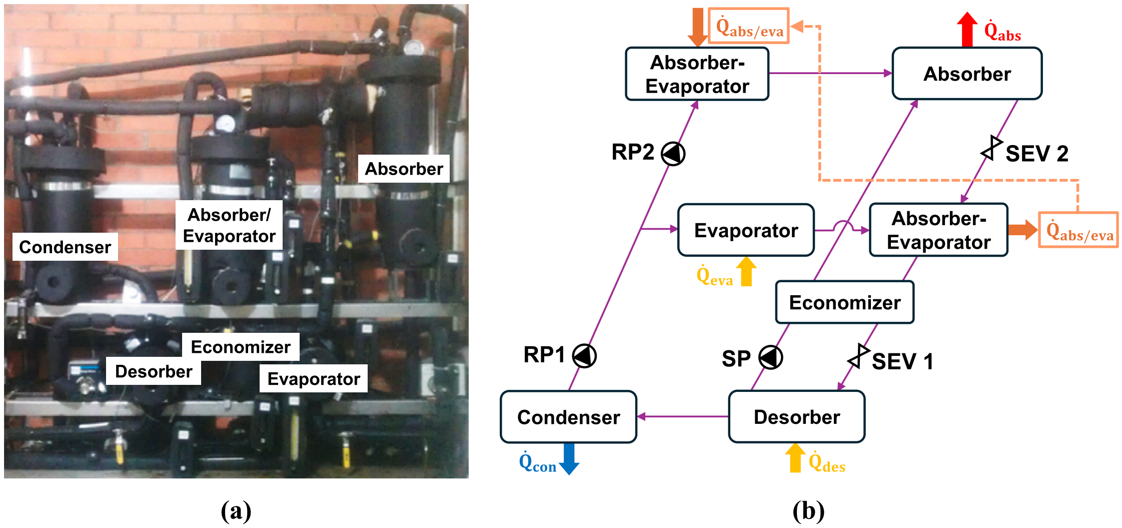

Fig. 23. A water/LiBr double AHT (DAHT, Type II heat pump) laboratory prototype developed by Rivera et al. [140]. (a) Photo of prototype external view; (b). DAHT cycle layout.

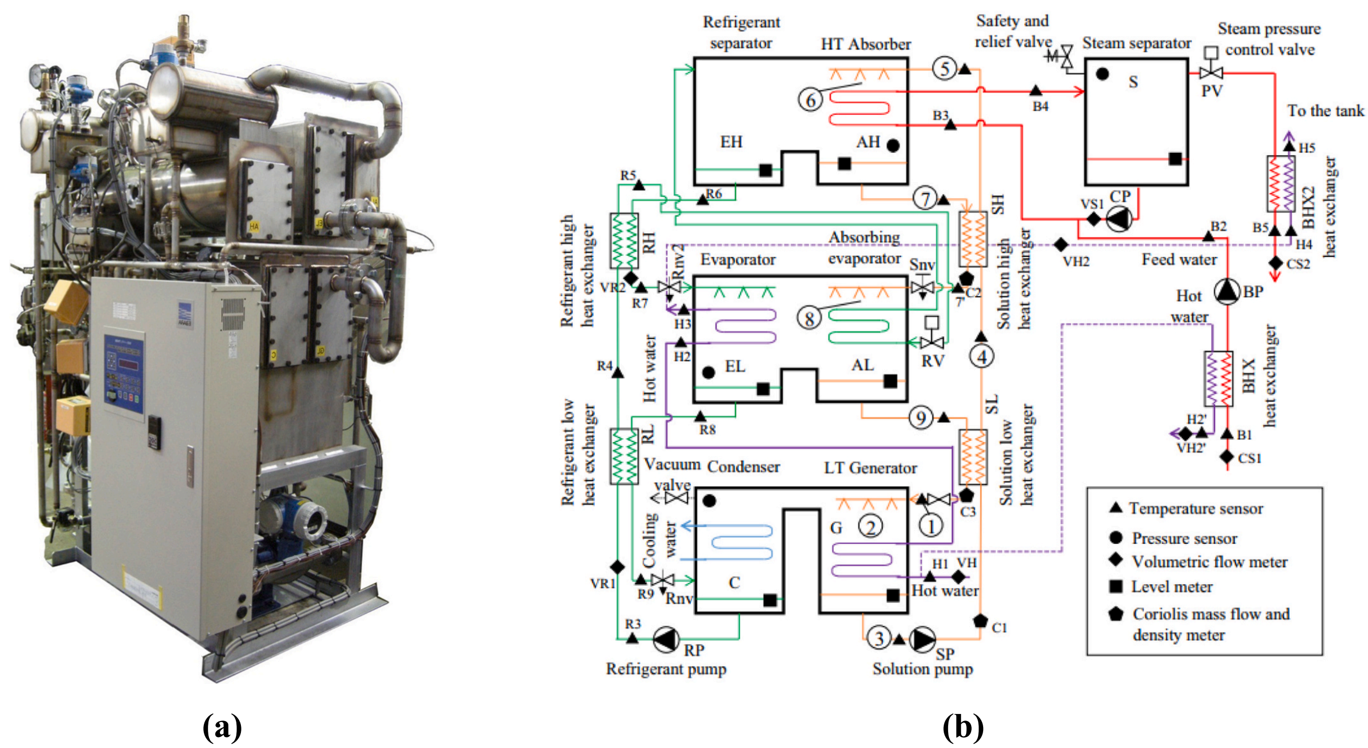

Fig. 24. A prototype of small-scale water/LiBr double-lift AHT (DLAHT, Type II heat pump) developed at Waseda University (Japan) [141]. (a) prototype external view; (b) prototype flow schematic of the experimental setup.

systems available, typically achieving COPs between 0.35 and 0.50. While single-stage absorption systems dominate the market, ongoing R&D in multi-stage technologies promises higher temperature lifts and improved performances (Table 6).

The global deployment of ACHPs, AHPs, and AHTs has shown promising applications in various industrial sectors, with major contributions to onsite waste heat recovery and overall energy efficiency improvements in food processing industries. The ammonia/water ACHPs developed by Hybrid Energy AS (now Sabroe Johnson Controls) have been installed across various industries, including dairies, biogas plants, and food processing. These heat pumps have demonstrated long-term reliability, with more than 600,000 operational hours across over 20 units installed globally. One of the key aspects of ACHPs is their integration into industrial energy recovery projects. For example, at the TINE SA dairy processing plant in Norway, the GreenPAC ACHP is used for hot water supply in dairy processes such as pasteurization and CIP operations. This system, along with ammonia chillers and heat pumps, has enabled the plant to achieve an electrical heating COP of 5.4, demonstrating high overall energy efficiency. Similar installations, such as the Borregaard ASA bio-refinery and the Frevar KF wastewater treatment plant, have also benefited from significant energy savings up to 60 GWh annually through the use of ACHPs to preheat feedwater and supply hot water for biogas production. In DH applications, such as in Denmark and South Korea, ACHPs recover waste heat from various

Table 6
Detail comparison between ammonia/water ACHPs, water/LiBr AHPs, and water/LiBr AHTs.

Technology	Ammonia/water ACHP	Water/LiBr AHP	Water/LiBr AHT
Heat source temperature	−10–90 °C	10–70 °C	60–150 °C
Heat supply temperature	Up to 160 °C	Up to 100 °C	Up to 185 °C
Driving energy type/source	Electricity	Hot water, Steam, Exhaust gas, Flue gas, and Fuels (NG, Oil, Diesel, etc.)	Waste hot water, Exhaust steam, Geothermal water, etc.
COP	3.4–7.3(electrical heating COP)	1.65–1.8(thermal heating COP)	0.33–0.48(thermal heating COP)
Heating capacity	500–10,000 kW	200–70,000 kW	150–15,000 kW
Commercial availability	Established (e.g., Sabroe-Johnson Controls (formerly from Hybrid Energy AS), AGO GmbH Energie + Anlagen)	Widely available(e.g., Broad, Ebara, Johnson Controls-Hitachi, Thermax, World Energy)	Widely available (e.g., Ebara, Johnson Controls-Hitachi, Shuangliang, Thermax,World Energy)
Key Challenges	High compressor discharge temp., lubricant issues, design of efficient absorber	Crystallization, corrosion at high temps	Crystallization, corrosion at high temps, design of efficient absorber

sources, including concentrated solar power plants and cooling water, delivering hot water for heating applications. These deployments not only enhance energy efficiency but also reduce carbon emissions, with some plants realizing reductions of several hundred metric tons of CO_2 per year. The Løgumkloster Fjernvarme plant in Denmark, for instance, has used ACHPs to recover waste heat from its solar power plant, resulting in reduced natural gas consumption and lower emissions.

Globally, the uptake of water/LiBr-based AHPs and AHTs has been similarly increasing and deployed in various industrial sectors and power plants. For instance, in Austria, a CNIM single-effect AHP recovers waste heat from flue gas condensation, supplying heat for biogas plant operations. In South Korea, Broad single-effect AHPs have been implemented in multiple thermal power plants and industrial applications, including district heating and a dyeing process mill, demonstrating their versatility across different heat source temperatures. China has also seen considerable deployments, with the Yanshan Petrochemical Corporation leading the way with an industrial-scale AHT to recover waste heat for synthetic rubber production. The success of this initial system, which achieved a reduction in steam consumption by 59 %, led to the expansion of the system at the plant. Other industrial applications in China and beyond (e.g., in Italy and Germany) include photovoltaic cell manufacturing and food processing, where AHTs are used to recover waste heat for various processes, including drying and cooking. These global applications demonstrate the gradual growing potential of absorption-based heat pumps in enhancing energy efficiency, reducing GHG emissions, and contributing to sustainable industrial process heating operations.

The new development and optimization of ammonia/water ACHPs are progressing with several prototypes built and tested globally. Particularly, prototypes with heating capacities ranging from 50 kW to 1 MW have demonstrated the potential for upgrading waste heat and supplying high-temperature process heat. One key challenge in ammonia/water ACHPs is the high discharge temperature of the compressor, which can lead to lubricant degradation and component failure (e.g., compressor seal). Oil-free operation, using approaches such as wet compression, is attracting interest, as it eliminates lubricant-related issues and improves performance. Moreover, research on wet compression, particularly using ammonia/water mixtures, has shown promising results, such as a 15 % increase in COP. Despite the progress, the high discharge temperature and pressure requirements for high-temperature heat supply remain limiting factors for achieving the desired operating conditions. These technical challenges continue to drive innovation in compressor technologies, including oil-free compressors and wet compression approaches, to improve the heat pump system efficiency, reliability, and extend operational range.

Recent advancements in AHTs have led to significant improvements in upgrading low-grade industrial waste heat. The Indus3Es Horizon 2020 project developed a single-stage water/LiBr AHT that achieved a thermal heating COP of 0.45, with a heat source at 95 °C and heat supply at 130 °C, using innovative adiabatic absorption methods and a non-condensable gas (e.g., air) purging system to enhance performance. Prototypes for direct steam generation showed thermal heating COPs between 0.40 and 0.48, supplying steam at temperatures up to 125 °C. Ammonia/water AHTs also demonstrated thermal COPs of 0.33–0.47, operating with heat sources from 60–95 °C and temperature lift up to 25 °C. Advanced water/LiBr AHT prototypes have demonstrated higher temperature lifts (e.g., 74 °C) compared to single-stage AHT (typically 40–50 °C), achieving thermal heating COPs of up to 0.33. These prototypes have enhanced heat transfer using surfactant additives and are designed to overcome key challenges in high-temperature operations, such as crystallization and corrosion. Future research developments, such as the ongoing ZIMBA EU project's integration of a two-phase ejector, aim to enhance system stability, extend operational ranges, and improve performance. These innovations are expected to accelerate the practical deployment of AHTs in high-temperature process heating applications.

7. Summary and perspective

7.1. Conclusion

Absorption-based heat pumps are a sustainable and attractive solution to upgrade low-temperature heat sources to a useful temperature level for various industrial applications. There are three types of absorption-based heat pumps; absorption heat pump (Type I heat pump, AHP), absorption heat transformer (Type II heat pump, AHT), and absorption-compression heat pump (ACHP). These heat pumps use natural working fluids such as water/LiBr and ammonia/water mixtures, which are environmentally friendly (no GWP and ODP). This article has reviewed the state of the art of absorption-based heat pump systems and technologies for industrial heating applications ($\geq$ 80 °C).

The AHPs currently available are based on single-stage water/LiBr technologies that are both direct-fired and indirect-fired (using hot water, steam, or exhaust gas). These AHPs (TRL 9) are limited to a maximum heat supply temperature of 100 °C with a temperature lift up to 50 °C. Thermal heating COPs are between 1.65 and 1.80 with a typical value of about 1.7, and a single unit has a heating capacity up to 70 MW. The current AHTs (TRL 9) are also based on single-stage water/LiBr technology with a maximum heat supply temperature of 185 °C and a temperature lift of up to 50 °C. The thermal COPs are between 0.33 and 0.48 with a typical value of around 0.45, and a single unit has a heating capacity of up to 15 MW. However, both technologies have a limited capacity to increase the heat supply temperature as well as the temperature lift because of, the solubility limit, corrosive nature, and thermal stability of the water/LiBr working pair. Another challenge of such heat pumps is compactness since systems based on classical absorption technology have large footprints.

The ammonia/water ACHPs (TRL 9) are presently available at a maximum heat supply temperature of 120 °C with a temperature lift between 25–60 °C. The electrical heating COPs of the ACHPs are in the range of 3.4–7.3 and have a heating capacity between 500–2300 kW based on single and twin reciprocating compressors. The main challenge is the lack of reliable compression technology with the ammonia (ammonia/water) working fluid to supply heat at higher temperatures (>120 °C). However, the newly developed ammonia/water ACHP (TRL 8–9) deliver heat up to 160 °C and temperature lift up to 110 °C, with heating capacities reaching up to 10 MW. Its modular design, containing up to three compression stages, facilitates efficient operation across a range of heat sources (−10 °C to 90 °C) including ambient air, cooling water, and exhaust air.

Finally, the use of absorption-based heat pumps in industries to recover waste heat has significant potential to improve energy efficiency and reduce the energy-related carbon footprint, thus contributing to the decarbonisation of the industries. However, considerable research is still required if the untapped potential of these heat pump technologies (particularly AHT and ACHP) is to be exploited to increase the heat supply temperature and the temperature lift to above current limits. Also, the reduction of their footprint is vital for the economic competitiveness of heat pumps with alternative heating sources. Consequently, research and development need to focus on the following key aspects: extending the solubility limits of water/LiBr solutions with suitable additives; taking measures to reduce the corrosivity of water/LiBr towards standard metal materials at high temperatures and concentrations, or using non-metal heat exchangers; improving the design of the system's components, particularly in the AHT and ACHP absorbers, to enhance the heat and mass transfer processes with various approaches (e.g., membrane contactors, solution atomization, etc.); and using advanced absorption cycle architectures to increase the temperature lift (> 50 °C) with double-lift AHPs and AHTs.

7.2. Perspective

To advance these technologies, we recommend the following research directions:

- Novel working fluids: Crystallization-free alternatives (e.g., refrigerant/deep eutectic solvents, refrigerant/ionic liquids) to overcome the drawbacks of tradition working fluids, including crystallization, high cost, and corrosion problems.
- Component optimization: Enhanced desorber/absorber designs using membrane contactors or microchannel structure to improve heat and mass transfer.
- Advanced cycles: advanced configuration (e.g., multi-stage and multi-effect cycles) and hybrid configurations to achieve performance improvement, validated through industrial pilots.
- Compressor technology: Oil-free, high-temperature compressors capable of withstanding high discharge temperatures, enabling heat pumps to target 150–200 °C applications.
- Sector-Specific studies: Comparative analyses across heat sources and industries to optimize system designs and deployment strategies, addressing review gaps.

By overcoming current barriers, absorption-based heat pumps can unlock their potential, significantly contributing to the decarbonization of industrial process heating and supporting global sustainability goals.

CRediT authorship contribution statement

Dereje S. Ayou: Writing – original draft, Validation, Software, Methodology, Investigation, Conceptualization. **Wei Wu:** Writing – review & editing. **Alberto Coronas:** Writing – review & editing, Supervision, Resources, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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