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A hybrid resorption-compression heat transformer for energy storage and upgrade with a large temperature lift

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HIGHLIGHTS

- A novel hybrid heat transformer is presented for a large temperature lift.
- The heat transformer outputs the heat higher than 150 °C with the input lower than 90 °C.
- Mass ratio and global conversion rate have large influence on real performance.
- Hybrid heat transformer technology is prospective for the heat reuse.

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ABSTRACT

Heat transformers reveal significant potential for primary energy savings in domestic and industrial processes, which can use different heat sources as driving force to provide the heat or cooling. In this paper, a hybrid resorption-compression heat transformer is presented, which aims to upgrade the heat source e.g. industrial waste heat or solar energy with a large temperature lift. Performance of hybrid heat transformer is also compared with that of multi-stage sorption type. Results indicate that with heat source temperatures ranging from 40 °C to 90 °C, energy and exergy efficiencies of hybrid heat transformer decrease from 0.429 to 0.403 and from 0.8 to 0.64, respectively. Energy efficiency of hybrid type is a bit lower than that of basic resorption transformer but almost double higher than that of multi-stage cycle. For different operating parameters, mass ratio and global conversion rate have larger influences on thermal performance than isentropic efficiency of compressor. Also hybrid resorption-compression heat transformer is prospective for domestic heat application through the integration with solar photovoltaic thermal collector. When heat output temperature ranges from 50 °C to 70 °C, it could ensure that the heat density is higher than 1000 $kJ\cdot kg_{am}^{-1}$ with an energy storage function.

1. Introduction

Heating is one of the major constituents of our energy use: over 75% of the final energy use in building and industry is in heating [1]. Meanwhile, statistics indicate that for the chemical and refinery industry in European countries e.g. the Netherlands, over 100 PJ of waste heat per year is actively released in the temperature range between 50 °C and 160 °C [2]. More efficient use of heat has a major impact on our total energy use and our carbon footprint. Heat transformers play crucial roles in the industrial heat recovery of low-grade energy resources [3], which are effective for upgrading the temperature of low-grade heat to a higher temperature level. For sorption systems, heat transformer is also known as the second type of heat pump [4]. Fig. 1 indicates the current and next generation heat pump/transformer technologies in terms of their heat sources and demands, which reveal vast potentials in a large temperature range of the applications e.g. space heating, food processing and chemical industry refineries [5,6]. Current technologies include close-cycle/mechanic vapor compression heat pumps and lithium bromide water sorption heat transformer while next generation technologies are hybrid heat transformer, electricity/gas fired thermoacoustic heat pump, thermochemical heat transformer, and hybrid-cycle vapor compression heat pump.

Compared with vapor compression heat pumps [7], sorption heat transformer technologies have been identified by the International Energy Agency (IEA) as renewable heating based systems for high

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Nomenclature

c_p	specific heat (kJ·kg^{-1}·K^{-1})
E	exergy (kJ)
h	specific enthalpy (kJ·kg^{-1})
M	mass of composite sorbent (kg)
m	mass of ammonia (kg)
P	pressure (Pa)
Q	heat (kW)
T	temperature (°C)
w	work input (kJ·kg^{-1})
X	sorption capacity (kg·kg^{-1})

Greek letters

Δh	reaction enthalpy of sorbent (J·mol^{-1})
Δs	reaction entropy of sorbent (J·mol^{-1}·K^{-1})
η	efficiency
ψ	global conversion rate
φ	mass ratio between reactor and adsorbent

Subscripts

a	adsorbent
am	ammonia
c	cooling
com	compression
e	electricity
en	energy
ex	exergy
h	heating
i	ideal
in	input
ma	mass
out	output
r	reaction
re	reactor
rea	real
S	solar
s	sensible
t	tested

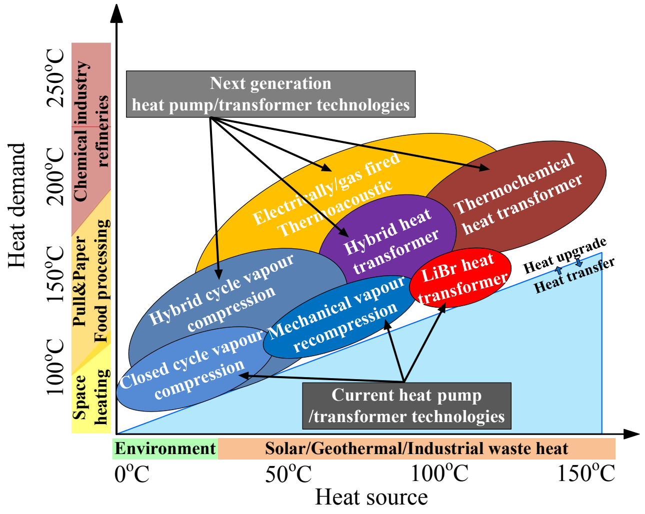
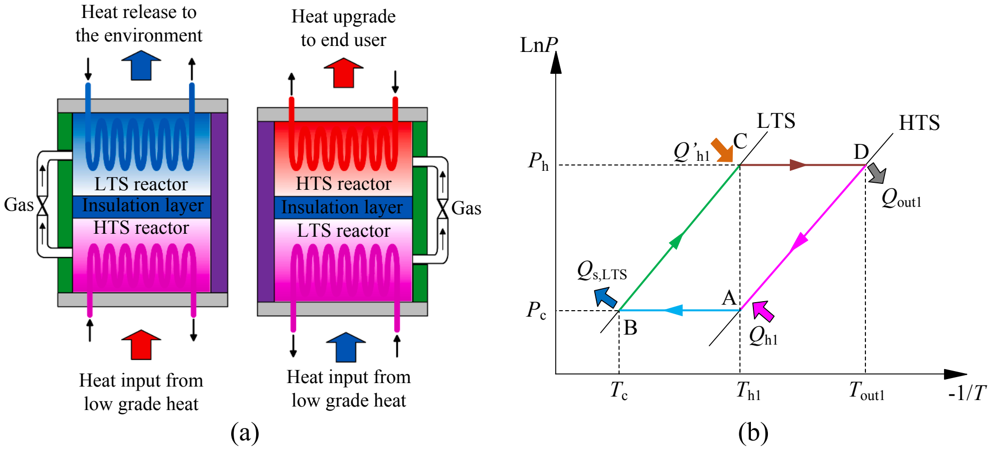


Fig. 1. Heat pump/transformer technologies and their operating temperatures.

temperature applications which enable the efficient use of renewable heat [8]. Liquid-gas sorption heat transformers have been widely investigated based on energy upgrade working mode [9]. Some lithium bromide water systems have been commercialized in the last decades [10]. Comparably, solid-gas sorption heat transformers are gathering momentum due to their advantages of no crystallization problems, simple structure and stable working temperature [11]. Considering the limitation of solid-gas sorption heat transformers e.g. system safety and flexibility, resorption type has drawn significant attractions in recent years [12,13]. As indicated in Fig. 2, the basic resorption heat transformer consists of a reactor with low temperature sorbent (LTS) and a reactor with high temperature sorbent (HTS), which are alternately charged and discharged [14]. During the charge phase (A-B), HTS reactor is heated by low grade heat Q_{h1} e.g. solar or industrial heat, resulting in the release of gaseous sorbate from HTS reactor. During energy upgrade phase (B-C-D), the process is reversed by heating LTS reactor with low grade heat Q'_{h1} ($\leq Q_{h1}$) once all of the sorbate is adsorbed by the LTS. This allows sorption of sorbate by the HTS whilst sorbate desorbs from the LTS. HTS could supply the heat Q_{out1} with a temperature higher than heat source temperature T_{h1}. Since the structure is similar to an electrical battery, it is also termed as thermal cell or battery which has low system pressure without liquid ammonia compared with basic sorption type [15].

Table 1 compares vapour compression heat pump with solid-gas



(a) (b)

Fig. 2. Concept of a basic resorption heat transformer (a) schematic; (b) *P-T* diagram [16].

Table 1
Comparison between vapor compression heat pump and solid-gas sorption heat transformer.

Type	Working fluid	Heat source temperature (°C)	Max. temperature lift (°C)	Compactness	Thermal Stability
Compression	Refrigerant	Lower than 90	30	High	High
Sorption	Ammonia, water, etc.	Higher than 120	60	Moderate	High

sorption heat transformer in terms of working fluid, heat source temperature, maximum temperature lift, compactness and thermal stability. For solid-gas sorption heat transformer, temperature lift is usually acceptable but the required heat source temperature is relatively high i.e. more than 120 °C [17]. Although multi-stage or cascading technology is the feasible solution, efficiencies of such systems are undesirable since more reactive salts are adopted [18]. For instance, Li et al. [19] proposed several concepts of solid-gas sorption heat transformer through four or five chemical working pairs. The theoretical results indicated good thermal performance for energy storage and upgrade. After that, their team experimentally investigated the sorption heat transformer for a large temperature lift [20]. The highest value of 65 °C was obtained. However, heat loss cannot be avoided in the process of internal heat recovery between two groups of working pairs. Given these factors of temperature lift, energy efficiency and number of working pairs, one good solution is to maintain the temperature lift while reducing heat source temperature to obtain a better performance based on a group of working pair. It is widely acknowledged that vapor compression heat pump has a relatively low heat input temperature and a high working efficiency [21]. Under this scenario, the advantages of these two types are combined to generate a high temperature lift by consuming a relatively small amount of work or electricity [22].

The advantage and feasibility of hybrid absorption compression heat transformer have been demonstrated by several researches [23,24]. Comparably, only a few research studies concentrate on hybrid solid sorption compression technologies for various outputs i.e. modified solid-gas sorption thermal battery. For energy storage and trigeneration, Bao et al. [25] proposed a chemisorption cycle that stored mechanical or electrical power through compression process. High energy storage density could be obtained by this novel thermal cycle. Godefroy et al. [26,27] comprehensively investigated several sorption cycles for power and refrigeration cogeneration as well as electricity storage and output by using a variety of working pairs. The most favourable configuration and adsorbent were screened and selected to meet the requirements in various applications. For energy upgrade with a large temperature lift, Hirota et al. [28] developed a novel hybrid solid-gas sorption heat transformer by introducing a mechanical booster pump. It was demonstrated that the proposed pump can achieve a heat output performance up to 1.6 times higher than that of the basis type. Compared with booster pump, the compressor is more suitable for sorption system especially by using ammonia as working fluid. Van der pal et al. [29] from Energy research Centre of the Netherlands (ECN) initiated the concept by extension the sorption systems with a compressor which attempted to provide more flexibility. Later, ECN conducted a techno-economic analysis of this hybrid heat transformer. It was indicated that hybrid heat-driven compression cycles could operate at lower heat source temperatures by introducing compressors [30]. However, the results mainly focused on the feasibility of the hybrid system which expected and underpinned more researches in the future. Gao et al. [31] investigated a pressure boost thermochemical sorption heat pump by using the same kind of sorbent in two reactors. Compared with traditional sorption heat pump, the system was able to operate continuously. However, the temperature lift was still limited. Based on the previous literatures, some insights could be summarised as follows:

1. Hybrid sorption-compression heat transformers are gathering the momentum due to their wide applications.
2. Most research studies on hybrid solid-gas sorption heat transformer focus on power output and tri/cogeneration by using various operating modes, e.g. separated and combined modes.
3. Very few research studies on hybrid solid-gas sorption heat transformer have been conducted for energy storage and upgrade which target a large temperature lift to be reused in the processes.

Capacity increment and system continuity are regarded as the main performance indicators for hybrid sorption cycles. However, these parameters are sometimes restraint with temperature lift. This paper aims to comprehensively investigate the concept of a hybrid resorption-compression heat transformer with a large temperature lift, which is achieved by integrating compressing process into resorption energy charging and upgrading process. Three research levels are progressively conducted in this analysis i.e. theoretical thermal cycle evaluation, sensitivity analysis using key parameters and an integrated application with solar photovoltaic thermal collector (PVT). The hybrid heat transformer cycle is also compared with multi-stage sorption cycle to further illustrate its advantage. The framework of this paper is illustrated as follows. Concepts of hybrid resorption-compression and multi-stage heat transformer are indicated in Section 2. Methodology to evaluate the heat transformer is elaborated in Section 3. Results and discussions of hybrid heat transformer with three research levels are indicated in Section 4 followed by the conclusions in Section 5.

2. Solid-gas sorption heat transformers

2.1. Hybrid resorption-compression heat transformer

Fig. 3 indicates the concept of hybrid resorption-compression heat transformer. The main difference between basic resorption heat transformer and hybrid type is the integration of a compressor between HTS and LTS reactor. As shown in Fig. 3a, two working processes are illustrated as follows: in the charging process, HTS is heated by low grade heat while the compressor is driven by the off-grid or renewable electricity. The refrigerant is desorbed from HTS reactor to LTS reactor, and then sorbed by releasing its sorption heat to environmental heat sink. Compared with the basic resorption heat transformer, a compressor can be used to pressurise the vapour and to assist the desorption process when heat supplied to HTS reactor does not have the enough high temperature. Under this scenario, the desorption temperature of the hybrid type could be reduced. Additionally, both low grade heat and electricity can be converted to chemical potential and be stored between sorption reactors. In the discharging and energy upgrade process, low grade heat can be utilised for the decomposition of LTS reactor and the desorbed ammonia vapour has a relatively high pressure and is sorbed by HTS reactor. Sorption heat is released with sorption temperature higher than heat source temperature. During this process, the compressor could further increase the output temperature by consuming electricity.

Due to monovariant characteristic of chemisorption working pairs, operating pressure only corresponds with operating temperature. Fig. 3b indicates *P-T* diagram of hybrid resorption-compression heat transformer. During the charging process, HTS is heated at point A′ by importing the heat Q_{h2}, and meanwhile off-grid electricity W_e is inputted to pressurize the ammonia from point A′ to point B′. LTS is cooled from point C to point B. Then ammonia could be desorbed from HTS reactor and sorbed by LTS reactor from point B′ to point B releasing the sorption heat $Q_{r,LTS}$. In the discharging and energy upgrade process, LTS is heated

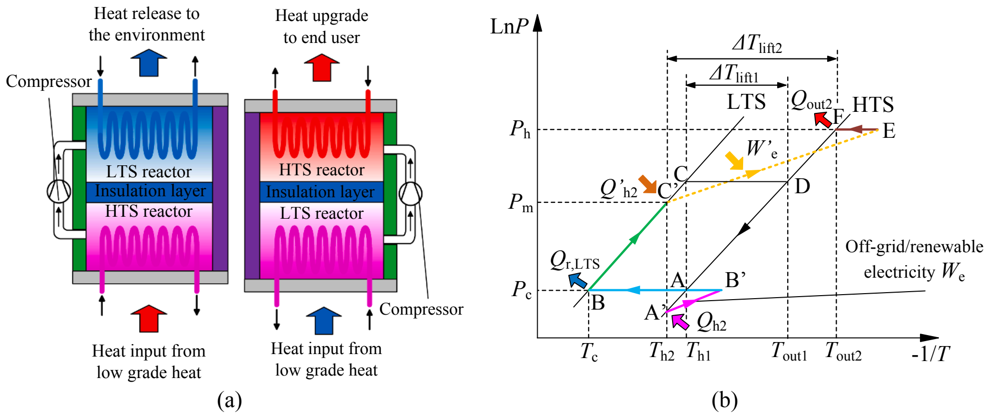


Fig. 3. Concept of hybrid resorption-compression heat transformer (a) schematic; (b) *P-T* diagram.

by low grade heat Q'_{h2} from point B to point C′. By consuming the electricity of the compressor W'_e, the sorption process proceeds from point E to point F to supply the heat Q_{out2}. As mentioned in Fig. 2, the basic resorption heat transformer cycle is A-B-C-D-A. Comparably, the hybrid resorption-compression heat transformer cycle is A′-B′-B-C′-E-F-A′. The heat input temperature of point A could be reduced to that of point A′ i.e. from T_{h1} to T_{h2}. The output temperature T_{out1} at point D is increased to T_{out2} at point F. One striking fact is that temperature lift is further increased from ΔT_{lift1} to ΔT_{lift2} as a result of both heat input temperature reduction and output temperature lift. By consuming a small amount of electricity input, the upgraded heat could be reused for industrial process which has wider applications.

Fig. 4 indicates the equilibrium *P–T* reaction lines of different chemisorption working pairs which are used to explain the selection criterion for the hybrid resorption-compression heat transformer cycle [32]. Temperature constraints and maximum allowable pressure ratio of the compressor are two key parameters to determine the hybrid cycle. It is desirable to choose the cooling temperature T_c i.e. ambient temperature ranging from 10 °C to 30 °C, heat source temperature T_h ranging from 40 °C to 90 °C and output temperature T_{out} from 150 °C to 200 °C which are denoted as three coloured area. This is mainly because the low or ultra-low temperature heat source is targeted as it is usually to be wasted, and the heat could be reused in low-medium temperature heat source [33]. Reaction pressure is selected between 1×10^4 Pa and 4×10^6 Pa. The minimal pressure is required to avoid requiring very large compressor while the maximum pressure is chosen for the system safety. An isentropic efficiency of 0.75 is used to determine the work consumed by the compressor [34]. Besides, a maximum pressure ratio of the mechanical compressor is used as three, which is applied for the analysis. By using this pressure ratio, dynamic compressors could be adopted which are more efficient than using positive displacement compressors [35].

Reaction pressure based on cooling temperature i.e. points a, b, c, d is better to be as low as possible, which will result in a relatively low heat input temperature. Also, reaction pressure i.e. points e, f, g, h based on heat source temperature is suggested to be as high as possible which could lead to a higher output temperature. Considering these two reasons, Calcium chloride ($CaCl_2$) and Manganese chloride ($MnCl_2$) are suitable candidates for HTS and LTS resorption working pairs. Fig. 5 indicates *P-T* diagram of hybrid resorption-compression heat transformer by using $CaCl_2$-$MnCl_2$ working pair which is used for detailed illustration of this cycle. The cooling temperature is set as 30 °C and the heat source temperature is set as 70 °C. Then the heat output temperature could be calculated as 165 °C when a pressure ratio for the compressor is defined as three. The temperature lift could reach 95 °C when compared with that of the basic $CaCl_2$-$MnCl_2$ resorption heat transformer. Thus the hybrid heat transformer could be suitable for both industrial and solar applications.

2.2. Multi-stage resorption heat transformer

In order to further elaborate the novelty of hybrid resorption-compression heat transformer, a triple-stage resorption cycle is

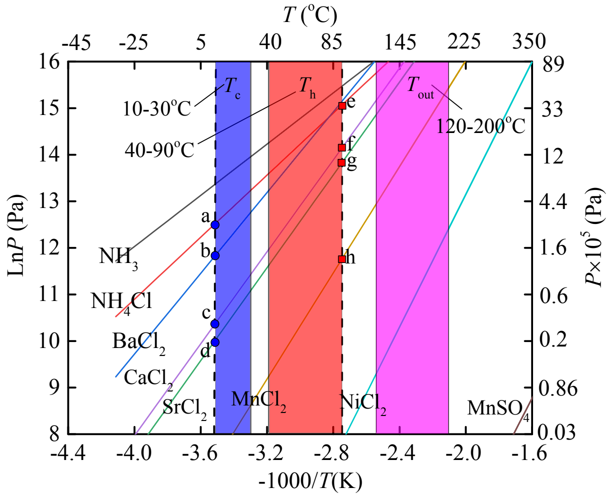


Fig. 4. Equilibrium *P–T* reaction lines of different chemisorption working pairs.

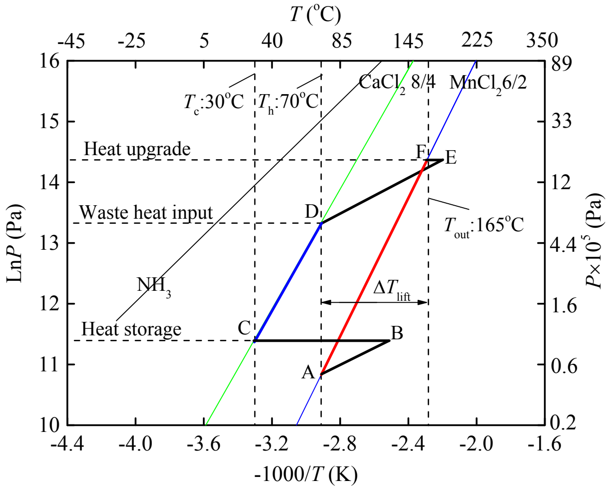
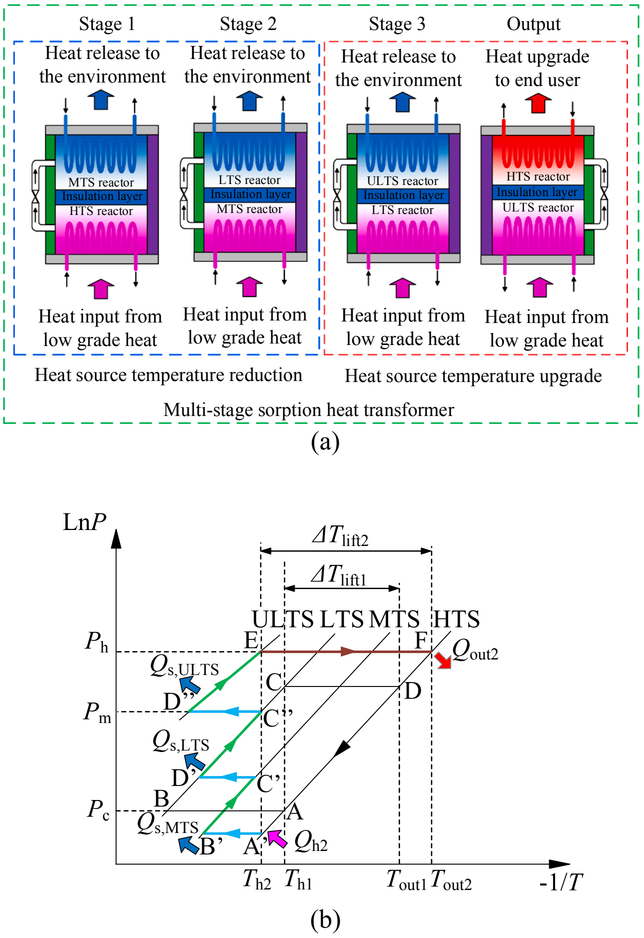


Fig. 5. *P-T* diagram of hybrid resorption-compression heat transformer by using $MnCl_2$-$CaCl_2$ working pair.



(a)

(b)

Fig. 6. Concept of triple-stage resorption heat transformer for large temperature lift.

presented and compared to achieve the large temperature lift without using the compressor which is shown in Fig. 6. Fig. 6a presents the schematic of the heat transformer while Fig. 6b indicates its *P*-*T* diagram. Different from hybrid resorption-compression heat transformer, triple-stage resorption type is composed of four sorption reactors with different solid sorbents i.e. ultra-low temperature sorbent (ULTS), LTS, medium temperature sorbent (MTS) and HTS. MTS and LTS are combined to reduce the heat source temperature while HTS and ULTS act as a group to upgrade the heat output temperature. These two groups are regarded to play a role as the compressor of hybrid resorption-compression heat transformer. In the charging process, HTS reactor is heated by external heat source Q_{h2}. Refrigerant is desorbed from HTS reactor to MTS reactor, and MTS reactor releases sorption heat $Q_{s,MTS}$ to environmental heat sink. It is observed that heat source temperature at point A′ is lower than that at point A. Then MTS and LTS reactor are successively heated by the same heat source at C′ and C″ while sorption heat is similarly released to the environmental heat sink at D′ and D″. The refrigerant is eventually sorbed by UTLS. During the discharging process, UTLS is heated by the heat source and the desorbed refrigerant with high temperature and pressure from ULTS will be sorbed by the HTS, which results in the higher heat output temperature T_{out2} at point F. Similarly, the temperature lift is further increased from ΔT_{lift1} to ΔT_{lift2} as a result of both heat input temperature reduction and the increase of output temperature.

Fig. 7 indicates *P*-*T* diagram of triple-stage sorption heat transformer by using $MnCl_2$, calcium bromide ($CaBr_2$), $CaCl_2$ and ammonium chloride (NH_4Cl) as a chemisorption working pair which is used for detailed illustration of this multi-stage cycle. In order to compare with the hybrid resorption-compression cycle in Fig. 5, the same temperature lift of 95 °C is considered i.e. the heat output temperature is set as 165 °C while heat source temperature is set as 70 °C. Three stages from a-b, c-d, e-f are used to reduce heat source temperature while the process g-h is to output the upgraded heat.

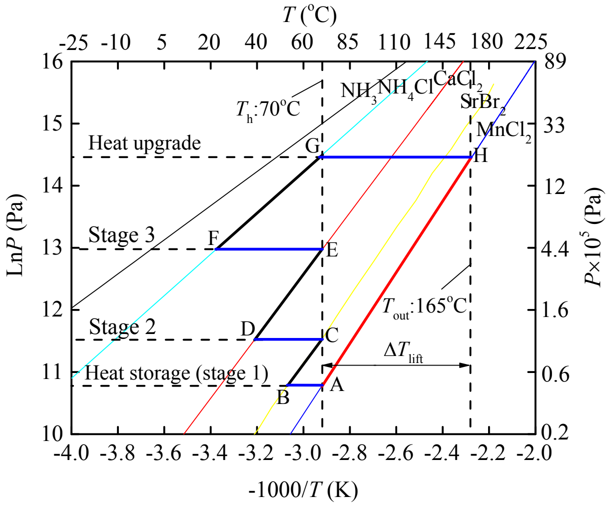


Fig. 7. *P-T* diagram of triple-stage resorption heat transformer using $MnCl_2$-$CaBr_2$-$CaCl_2$-NH_4Cl working pair.

3. Analytical methodology

3.1. Characterization of sorbents

Thermochemical reaction processes of the above selected solid sorbents with ammonia can be expressed as Eqs. (1)–(4). $MnCl_2$ 6/2 represents the process where $MnCl_2$ ammoniate reacts with ammonia from 6 mol to 2 mol. Table 2 shows the main parameters of selected chemical sorbents in terms of equilibrium desorption temperature, reaction enthalpy Δh, reaction entropy Δs, maximum sorption capacity and specific heat capacity. The real gas properties of the ammonia are provided by national institute of standard and technology (NIST). The equilibrium desorption temperature is evaluated at a heat sink temperature of 30 °C. The composite sorbent with expanded natural graphite (ENG) is applied for the analysis due to its stability in the real system. The parameters used have been reported in Ref. [36] in which thermal conductivity and permeability are in the range of 0.62–2.98 $W\cdot m^{-1}\cdot K^{-1}$ and 10^{-11}–10^{-14} m^2, respectively. Since heat and mass transfer performance are enhanced by ENG, the limitation within composite sorbents e.g. mass transfer block can be ignored at the relatively high working pressure. The metallic reactor is also taken into consideration. The required amount of salt depends on its molar weight, stoichiometry and the fraction of salt reacting during each working cycle [37].

$$\mathrm{MnCl_2\hat{A}\cdot 2NH_3 + 4NH_3 \leftrightarrow MnCl_2\hat{A}\cdot 6NH_3 + 4\Delta \mathit{h}_{MnCl2}} \tag{1}$$

$$\mathrm{SrBr_2\hat{A}\cdot 2NH_3 + 6NH_3 \leftrightarrow SrBr_2\hat{A}\cdot 8NH_3 + 6\Delta \mathit{h}_{SrBr2}} \tag{2}$$

$$\mathrm{CaCl_2\hat{A}\cdot 2NH_3 + 4NH_3 \leftrightarrow CaCl_2\hat{A}\cdot 6NH_3 + 4\Delta \mathit{h}_{CaCl2}} \tag{3}$$

$$\mathrm{NH_4Cl + 3NH_3 \leftrightarrow NH_4Cl\hat{A}\cdot 3NH_3 + 3\Delta \mathit{h}_{NH_4Cl}} \tag{4}$$

3.2. Performance evaluation of resorption cycles

The heat output of resorption cycles Q_{out} can be expressed as Eq. (5).

$$Q_{out} = Q_{r,HTS} - Q_{s,HTS} \tag{5}$$

Table 2
The main parameters of selected sorbents [38,39].

Salt	Desorption temperature (°C)	Δh (J·mol^{-1})	Δs (J·mol^{-1}·K^{-1})	Max. sorption capacity (kg·kg$_a^{-1}$)	c_p (J·kg^{-1}·K^{-1})
$MnCl_2$ 6/2	152	47,416	227.9	0.54	$4.184 * (16.2 + 0.052 * T)/M_{MnCl2}$
$SrBr_2$ 8/2	130	45,617	229.3	0.41	$4.184 * (18.1 + 0.00311 * T)/M_{SrBr2}$
$CaCl_2$ 8/4	86	41,403	229.7	0.61	$4.184 * (11.74 + 0.00233 * T)/M_{CaCl2}$
NH_4Cl 3/0	52	27,678	207.9	0.95	$4.184 * (9.8 + 0.0368 * T)/M_{NH4Cl}$

where $Q_{r,HTS}$ is reaction heat of HTS, kW; $Q_{s,HTS}$ is total sensible heat of HTS reactor part, kW.

The sensible heat of HTS reactor part $Q_{s,HTS}$ in Eq. (5) could be expressed as Eq. (6), which consists of ENG, sorbent, ammonia and sorption reactor.

$$\begin{aligned} Q_{s,\mathrm{HTS}} &= Q_{s,\mathrm{ENG}} + Q_{s,\mathrm{salt}} + Q_{s,\mathrm{am}} + Q_{s,\mathrm{re}} \\ &= [(mc_p)_{\mathrm{ENG}} + (mc_p)_{\mathrm{salt}} + (mc_p)_{\mathrm{am}} + (mc_p)_{\mathrm{re}}] \times (T_{\mathrm{out}} - T_{\mathrm{h}}) \end{aligned} \tag{6}$$

where the first term in the right side of Eq. (6) is sensible heat consumed by ENG $Q_{s,ENG}$; the second and third terms are sensible heat consumed by sorbent $Q_{s,salt}$ and ammonia $Q_{s,am}$, respectively; the fourth term is sensible heat consumed by metal part of sorption reactor $Q_{s,re}$; T_{out} is the heat output temperature, °C; T_h is the heat source temperature, °C.

The output heat exergy E_{out} can then be calculated as Eq. (7).

$$E_{\mathrm{out}} = (1 - \frac{T_{\mathrm{c}}}{T_{\mathrm{out}}}) \times Q_{\mathrm{out}} \tag{7}$$

where T_c is the cooling temperature, °C.

The heat inputs of resorption cycles Q_{in} are different due to their different operating processes. For hybrid resorption-compression heat transformer cycle, the heat input is composed of HTS part Q_{in1} and LTS part Q_{in2}, which include the desorption heat and reaction heat according to Eqs. (8)–(10).

$$Q_{\mathrm{in}} = Q_{\mathrm{in1}} + Q_{\mathrm{in2}} \tag{8}$$

$$Q_{\mathrm{in1}} = Q_{\mathrm{r,HTS}} + Q_{\mathrm{s,HTS}} \tag{9}$$

$$Q_{\mathrm{in2}} = Q_{\mathrm{r,LTS}} + Q_{\mathrm{s,LTS}} \tag{10}$$

The sensible parts of heat inputs $Q_{s,HTS}$ and $Q_{s,LTS}$ in Eqs. (9) and (10) could be expressed as Eqs. (11) and (12).

$$\begin{aligned} Q_{s,\mathrm{HTS}} &= Q_{s,\mathrm{ENG}} + Q_{s,\mathrm{salt}} + Q_{s,\mathrm{am}} + Q_{s,\mathrm{re}} \\ &= [(mc_p)_{\mathrm{ENG}} + (mc_p)_{\mathrm{salt}} + (mc_p)_{\mathrm{am}} + (mc_p)_{\mathrm{re}} \times (T_{\mathrm{h}} - T_{\mathrm{c}})] \end{aligned} \tag{11}$$

$$\begin{aligned} Q_{s,\mathrm{LTS}} &= Q'_{s,\mathrm{ENG}} + Q'_{s,\mathrm{salt}} + Q'_{s,\mathrm{am}} + Q'_{s,\mathrm{re}} \\ &= [(mc_p)_{\mathrm{ENG}} + (mc_p)_{\mathrm{salt}} + (mc_p)_{\mathrm{am}} + (mc_p)_{\mathrm{re}} \times (T_{\mathrm{h}} - T_{\mathrm{c}})] \end{aligned} \tag{12}$$

For triple-stage resorption cycle for energy upgrade, the heat input Q_{in} could be expressed as Eqs. (13)–(17).

$$Q_{\mathrm{in}} = Q_{\mathrm{in1}} + Q_{\mathrm{in2}} + Q_{\mathrm{in3}} + Q_{\mathrm{in4}} \tag{13}$$

$$Q_{\mathrm{in1}} = Q_{\mathrm{r,HTS}} + Q_{\mathrm{s,HTS}} \tag{14}$$

$$Q_{\mathrm{in2}} = Q_{\mathrm{r,MTS}} + Q_{\mathrm{s,MTS}} \tag{15}$$

$$Q_{\mathrm{in3}} = Q_{\mathrm{r,LTS}} + Q_{\mathrm{s,LTS}} \tag{16}$$

$$Q_{\mathrm{in4}} = Q_{\mathrm{r,ULTS}} + Q_{\mathrm{s,ULTS}} \tag{17}$$

where sensible part of heat input is similar with that of the above hybrid cycle. The only difference is that temperature differences for Q_{in1}, Q_{in2}, Q_{in3} and Q_{in4} are in the range from T_h to T_c, T_h to T_B, T_h to T_D, and T_h to T_F in which T_B, T_D and T_F correspond to the temperatures at point B, D, and E.

Heat exergy input of different resorption cycles E_{in} could be expressed as Eq. (18).

$$E_{\mathrm{in}} = (1 - \frac{T_{\mathrm{c}}}{T_{\mathrm{h}}}) \times Q_{\mathrm{in}} \tag{18}$$

Power consumed by the compressors W_{com1}, W_{com2} could be expressed as Eqs. (19) and (20) in terms of different working processes in the hybrid cycle.

$$W_{\mathrm{com1}} = E_{\mathrm{w1}} = m \times (\mathrm{h}_{\mathrm{out1}} - \mathrm{h}_{\mathrm{in1}}) \tag{19}$$

$$W_{\mathrm{com2}} = E_{\mathrm{w2}} = m \times (\mathrm{h}_{\mathrm{out2}} - \mathrm{h}_{\mathrm{in2}}) \tag{20}$$

where h_{out} and h_{in} are the outlet and inlet enthalpy of ammonia vapor through the compressor, kJ·kg$_{am}^{-1}$.

The temperature lift of energy upgrade ΔT_{lift} can be defined as Eq. (21).

$$\Delta T_{\mathrm{lift}} = T_{\mathrm{out}} - T_{\mathrm{h}} \tag{21}$$

Energy efficiency η_{ex} and exergy efficiency η_{ex} of the cycles could be expressed as Eqs. (22) and (23):

$$\grave{E}_{\mathrm{en}} = \frac{Q_{\mathrm{out}}}{Q_{\mathrm{in}}} = \frac{Q_{\mathrm{out}}}{W_{\mathrm{com1}} + W_{\mathrm{com2}} + Q_{\mathrm{in}}} \tag{22}$$

$$\grave{E}_{\mathrm{ex}} = \frac{E_{\mathrm{out}}}{E_{\mathrm{in}}} = \frac{E_{\mathrm{out}}}{W_{\mathrm{com1}} + W_{\mathrm{com2}} + E_{\mathrm{in}}} \tag{23}$$

3.3. Parameters for sensitivity analysis

Thermal performance of the hybrid resorption-compression heat transformer cycle could be influenced by various factors e.g. isentropic efficiency of compressor, global conversion rate and heat and mass transfer performance. Three key variable parameters are then adopted to further illustrate the performance, in which global conversion rate and mass ratio are defined as follows.

It is acknowledged that the sorbent and working fluid could not be efficiently reacted due to working conditions in the real system. The global conversion rate ψ_{con} denotes the percentage of adsorbent that reacts with the refrigerant, which is used to indicate the incompleteness of the reaction. It could be defined according to Eq. (24).

$$\psi_{\mathrm{con}} = \frac{X_{\mathrm{rea}}}{X_i} \tag{24}$$

where X_{rea} and X_i are sorption capacities under real and ideal working conditions, kg•kg$_a^{-1}$.

Mass ratio between mass of sorption reactor and adsorbent φ_m is adopted as Eq. (25), which is used to evaluate the performance by considering the metal part in the real sorption system.

$$\varphi_{\mathrm{m}} = \frac{M_{\mathrm{re}}}{M_a} \tag{25}$$

where M_{re} and M_a are the mass of sorption reactor and adsorbent, kg.

3.4. An integrated application with solar PVT

Heat density of the hybrid resorption-compression heat transformer integrated with solar PVT can be defined as Eq. (26).

$$Heatdensity = \psi_{\mathrm{con,t}} \times \frac{Q_{\mathrm{out}}}{M_{\mathrm{a}}} \tag{26}$$

where M_{a} is the mass of HTS composite sorbent, kg. The tested global conversion rates are obtained based on the operation conditions and heat supply requirements.

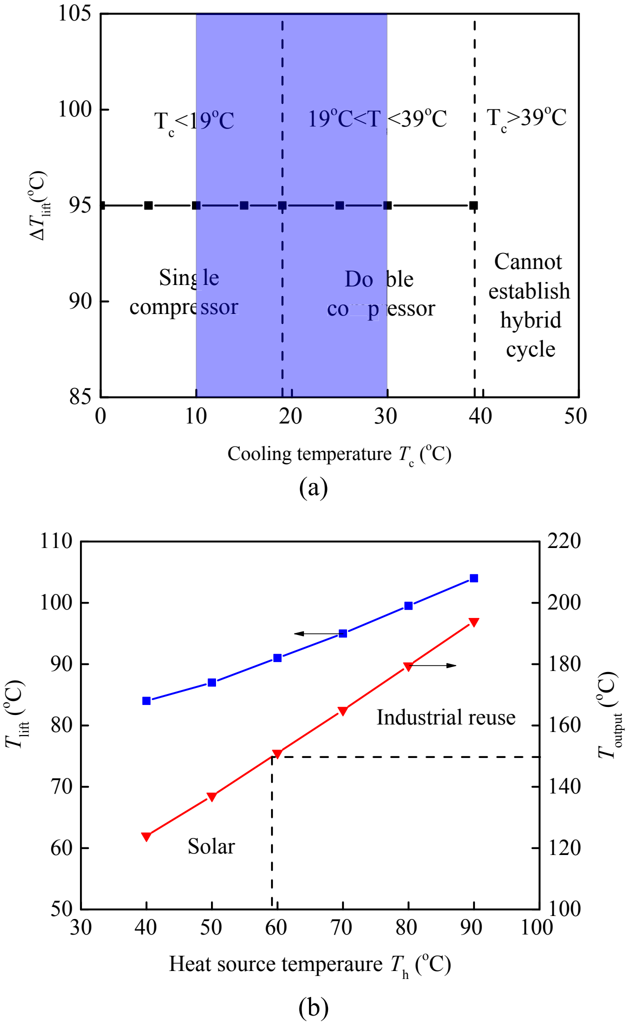
Energy efficiency of the hybrid heat transformer integrated with solar PVT can be expressed as Eq. (27).

$$\grave{E}_{\mathrm{en,S}} = \psi_{\mathrm{con,t}} \times \frac{Q_{\mathrm{out}}}{Q_{\mathrm{in}}} \tag{27}$$

4. Results and discussions

4.1. Thermal cycle evaluation

Since the temperature lift is considered as the dominant parameter for the hybrid resorption-compression heat transformer, it is first discussed under the conditions of the different cooling temperatures, heat source temperatures and heat output temperatures. Heat source temperature is related with heat output temperature but independent of the cooling temperature. Thus, the hybrid resorption-compression heat transformer could work with single compressor and double compressor modes, which are evaluated as shown in Fig. 8. Fig. 8a indicates the temperature lift of hybrid heat transformer under the conditions of different cooling temperatures. When cooling temperature varies from 10 °C to 30 °C, heat source temperature and heat output are kept constant, which result in the temperature lift of 95 °C. It is indicated that cooling temperature has no influence on the temperature lift. Also three different cooling temperature ranges can be found i.e. lower than 19 °C, 19–39 °C and higher than 39 °C. When the cooling temperature is higher than 39 °C, the hybrid cycle cannot be established due to the set-up limit compression ratio of 3. In the range from 19 °C to 39 °C, the hybrid cycle could be achieved as discussed in Fig. 5. When the cooling temperature is lower than 19 °C, only one compressor is required in the upgrading process. This is because the heat source temperature of 70 °C is high enough to drive the desorption process from $MnCl_2$ to $CaCl_2$. As shown in Fig. 8b, both output temperature and temperature lift increase with the increase of heat source temperature. When the heat source temperature increases from 40 °C to 90 °C, the results increase from 124 °C to 194 °C (output temperature) and 84 °C to 104 °C (temperature lift), respectively. The main reason is that the slope increases with higher heat source temperature, e.g. $MnCl_2$ is steeper than $CaCl_2$ which leads to the larger increment of temperature lift. In order to have a comprehensive understanding, cooling temperature range for the hybrid resorption-compression heat transformer is summarised in Table 3. When cooling temperature ranges from 10 °C to 30 °C, the combination of heat source and cooling temperature for hybrid heat transformer with two-stage compression could be 40/10 °C, 50/10–20 °C, 60/15–25 °C, 70/15–25 °C and 80/30 °C.



(a)

(b)

Fig. 8. Temperature lift under working conditions of different (a) cooling temperatures; (a) heat source temperatures.

Fig. 9 indicates the specific work consumption of the compressor for 1 kg of ammonia, in which Fig. 9a and Fig. 9b show the results in the charging and discharging processes. According to Table 3, only a few temperature combinations are suitable for the hybrid resorption-compression heat transformer by using two compressors when the cooling temperature ranges from 10 °C to 30 °C. For energy consumption in the charging process, specific work consumption ranges from 25.3 $\mathrm{kJ \cdot kg_{am}^{-1}}$ to 182.7 $\mathrm{kJ \cdot kg_{am}^{-1}}$. When the cooling temperature becomes higher, the specific work is increased due to the large compression ratio in the working process. In the discharging process, one cooling temperature corresponds to one heat source temperature. The specific work slightly increases with the higher cooling temperature. When cooling temperature increases from 10 °C to 30 °C, the specific work consumption ranges from 192.4 $\mathrm{kJ \cdot kg_{am}^{-1}}$ to 203.7 $\mathrm{kJ \cdot kg_{am}^{-1}}$.

Fig. 10 presents energy and exergy efficiencies of hybrid resorption-compression heat transformer under the condition of different heat source temperatures. It is indicated that energy efficiency gradually decreases with the increase of the heat source temperature. This is mainly because that heat input increases greatly with the increase of heat source temperature which makes it take a leading role in the energy efficiency. When heat source temperature increases from 40 °C to 90 °C, energy efficiencies of the hybrid heat transformer decrease from 0.429 to 0.403. As for exergy efficiency, it keeps constant first and then decreases. The main reason for this trend is that the heat with high output temperature results in a higher heat exergy output. When the heat source temperature increases, the heat input exergy further increases which results in a decrease trend. With the increase of heat source temperature from 40 °C to 90 °C, exergy efficiencies of the hybrid heat transformer range from 0.8 to 0.64. In order to have a clear

Table 3
Cooling temperature range for the hybrid heat transformer.

Heat source temperature (°C)	Output temperature (°C)	Cooling temperature range (°C)		
		One compressor is required	Two compressors are required	cannot establish the cycle
40	124	$T_c < -5$	$-5 \le T_c \le 11$	$T_c > 11$
50	137	$T_c < 2$	$2 \le T_c \le 21$	$T_c > 21$
60	151	$T_c < 11$	$11 \le T_c \le 29$	$T_c > 29$
70	165	$T_c < 19$	$19 \le T_c \le 39$	$T_c > 39$
80	179.5	$T_c < 27$	$27 \le T_c \le 43$	$T_c > 43$
90	194	$T_c < 36$	$36 \le T_c \le 58$	$T_c > 58$

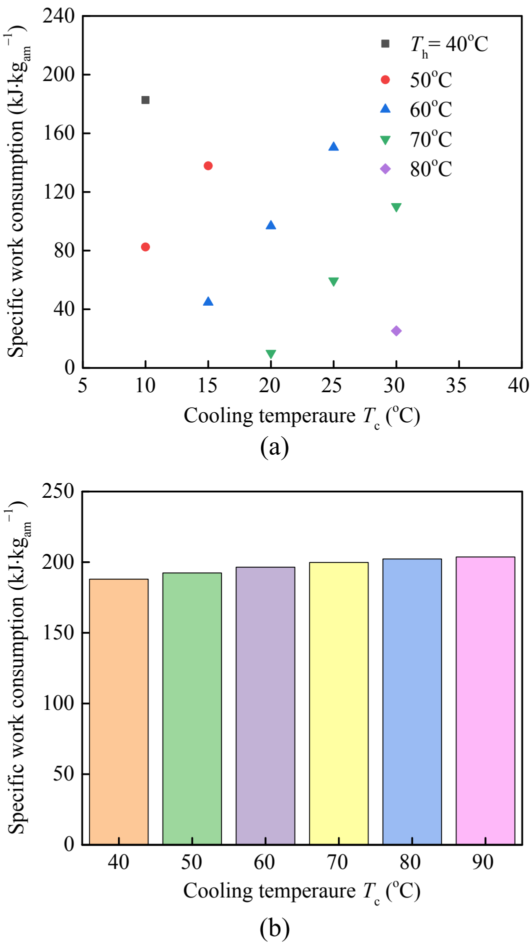


Fig. 9. Specific work consumption of hybrid heat transformer by using $MnCl_2$-$CaCl_2$ working pairs in terms of (a) in the charging process; (b) in the discharging process.

understanding among the different resorption transformers, their performance is compared in terms of energy efficiency, exergy efficiency and compactness as shown in Table 4. It is demonstrated that the temperature lift of hybrid sorption-compression and multi-stage resorption heat transformer are much higher than that of basic resorption transformer. The energy efficiency of hybrid heat transformer is a bit lower than that of resorption transformer, which is almost twice higher than that of multi-stage cycle. Similarly, exergy efficiency of the hybrid cycle is about 25.6% higher than that of multi-stage cycle. Also worth noting that compactness of the hybrid cycle is similar with that of basic resorption heat transformer due to the reduction of the sorption reactors.

4.2. Sensitivity analysis

This section investigates hybrid resorption-compression heat transformer by considering the key parameters under real working conditions. The isentropic efficiency of compressor, global conversion rate and mass ratio between reactor and adsorbent are used for sensitivity analysis due to their significant roles in the chemisorption systems. Under the condition of 70 °C heat source temperature and 30 °C cooling temperature, Fig. 11 shows energy and exergy efficiencies of the hybrid heat transformer based on different isentropic efficiencies of the compressor which range from 0.5 to 1. It is indicated that isentropic efficiency of compressor has a smaller influence on energy efficiency than on exergy efficiency due to the fact that electricity with high energy quality is consumed by the compressors in the hybrid heat transformer.

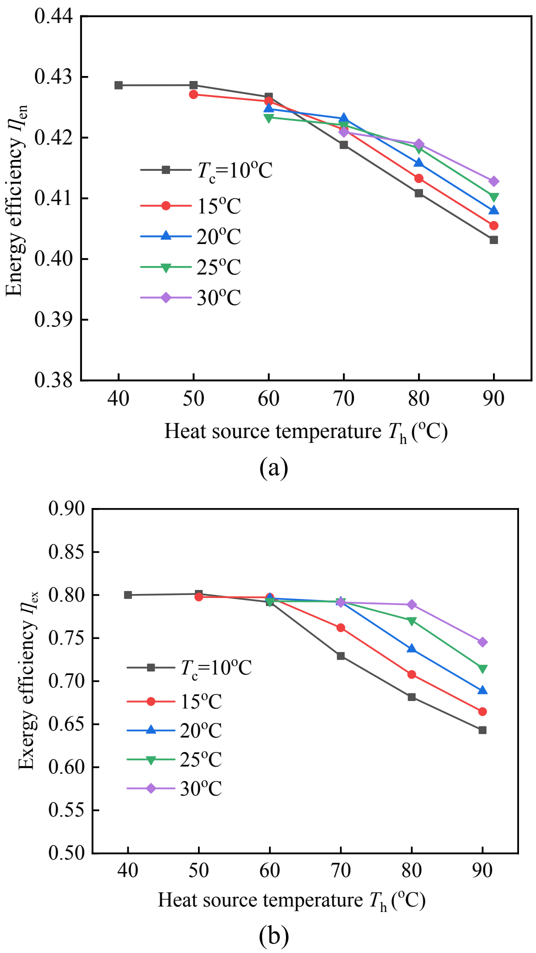


Fig. 10. Thermal performance of hybrid heat transformer by using $MnCl_2$-$CaCl_2$-NH_3 working pairs in terms of (a) energy efficiency; (b) exergy efficiency.

With the increase of isentropic efficiency of compressor from 0.5 to 1, energy efficiencies increase from 0.4 to 0.421 while exergy efficiencies increase from 0.597 to 0.791. It is extensively acknowledged that isentropic efficiencies of the compressor usually range from 0.5 to 0.7 under real working condition since the different compressing ratios are required. Thus, the performance of energy and exergy efficiencies could be improved by 3% and 20%, respectively, if the isentropic efficiencies of the compressor would be improved from 0.5 to 0.7.

Fig. 12 indicates energy and exergy efficiencies of hybrid resorption-compression and multi-stage heat transformers in terms of different global conversion rates. For theoretical thermal cycle evaluation in section 4.1, the global conversion rate is regarded as 1. Comparably, the real operating conditions for sorption systems result in the finite reaction duration i.e. the conversion rate is less than 1 due to the limited heat/mass transfer performance. When global conversion rates vary from 0.2 to 1, energy efficiency of the hybrid heat transformer is always higher than that of the multi-stage type whereas exergy efficiency has an intersection point between two resorption heat transformers. This is mainly because the electricity consumed by the compressors plays a more important role to evaluate the performance of hybrid cycle rather than metal part of the reactor. It is indicated that energy efficiencies of hybrid heat transformer and multi-stage type increase from 0.127 to 0.421 and 0.085 to 0.248 when the global conversion rates increase from 0.2 to 1. Exergy efficiencies of hybrid heat transformer and multi-stage type increase from 0.137 to 0.791 and 0.225 to 0.655, respectively. When the global conversion rates are higher than 0.56, exergy efficiency of multi-stage cycle is more advantageous than that of hybrid type. Under the real operating conditions, the global conversion rate is usually

Table 4
Performance comparison between different heat transformers.

Type	Heat source temp. (°C)	Heat output temp. (°C)	Temp. lift (°C)	Energy efficiency	Exergy efficiency	Compactness
Basic	87	152	65	0.455	0.825	High
Hybrid	70	165	95	0.421	0.791	High
Triple-stage	70	165	95	0.238	0.63	>2 times

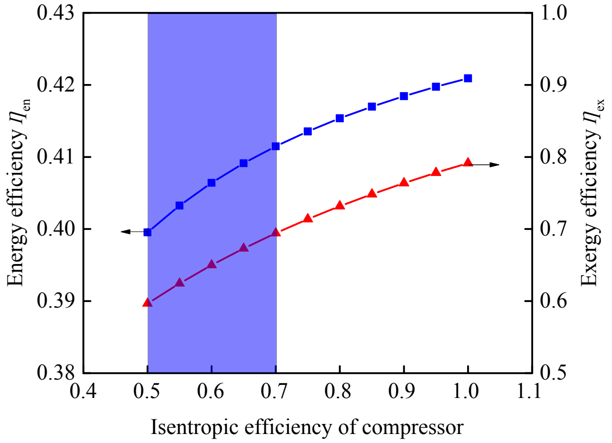


Fig. 11. Energy and exergy efficiencies of hybrid resorption-compression heat transformer vs. different isentropic efficiencies of the compressor.

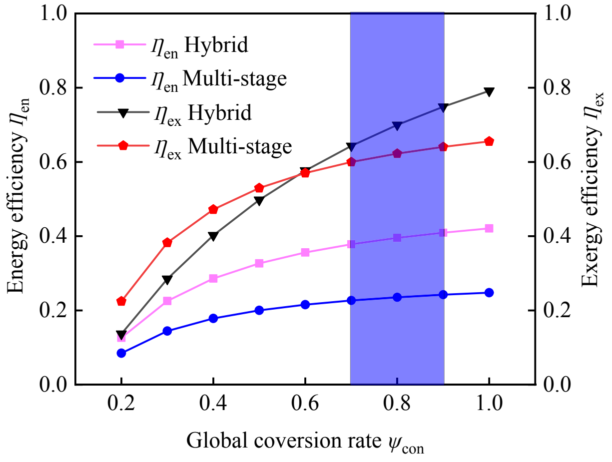


Fig. 12. Energy and exergy efficiencies of hybrid resorption-compression and multi-stage heat transformers vs. different global conversion rates.

controlled in the range from 0.7 to 0.9. In this range, energy and exergy efficiencies of hybrid heat transformer could be improved by at least 80% and 5% when compared with those of multi-stage type.

Fig. 13 indicates energy and exergy efficiencies of hybrid resorption-compression and multi-stage heat transformers in terms of different mass ratios, which are defined as the specific value between mass of sorption reactor and adsorbent in the sorption systems. With the increase of mass ratios, both energy and exergy efficiencies of resorption heat transformers remarkably decrease due to the increasing heat exergy input of metal part of the system. When mass ratios increase from 0 to 8, energy efficiencies of hybrid heat transformer and multi-stage type decrease from 0.421 to 0.196 and 0.238 to 0.106, respectively. Exergy efficiencies of hybrid heat transformer and multi-stage type decrease from 0.791 to 0.382 and from 0.63 to 0.279, respectively. In real sorption systems, mass ratio between sorption reactor and adsorbent always depends on various factors e.g. reactor type, sorbent type, manufacturing technology, etc. For chemisorption systems, mass ratio of three is a minimum value that can be achieved based on current technologies. Under this scenario, energy and exergy efficiencies of hybrid resorption-compression heat transformer could be improved by approximately 80% and 30% when compared with those of multi-stage type. It is expected to reduce mass ratio through optimal thermal design and novel adsorbent development so that a higher thermal efficiency of hybrid heat transformer could be ensured.

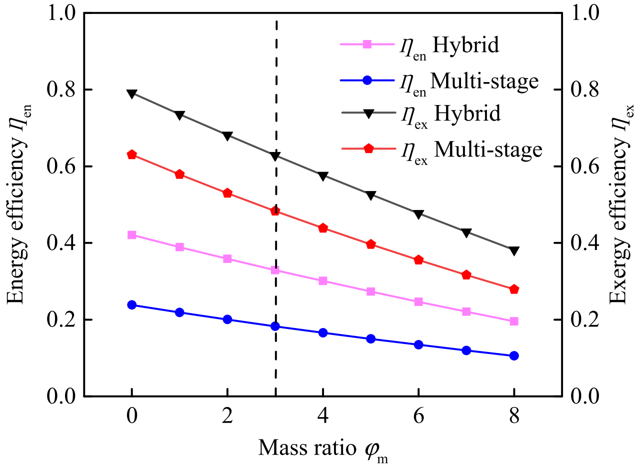
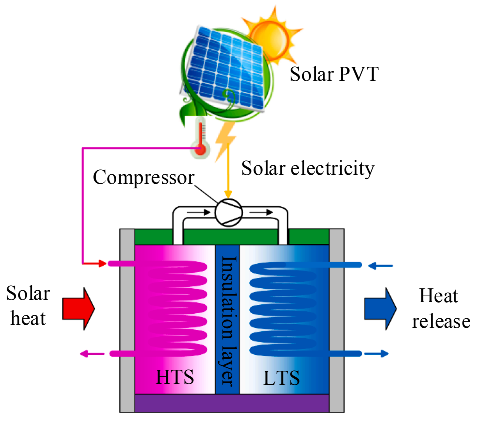


Fig. 13. Energy and exergy efficiencies of hybrid resorption-compression and multi-stage heat transformers vs. different mass ratios.

4.3. An integrated application with solar PVT

Except the main applications in the industrial sector, a very promising application of hybrid resorption-compression heat transformer i.e. integration of current solar PVT technology is presented and analyzed in this section. It could solve the problems of solar PVT e.g. low output temperature and small output power in winter, which are considered as the barriers for its further application. Fig. 14 indicates this integrated concept in both charging and discharging processes. In the charging phase, the water heated by the solar panel flows into HTS reactor and endothermic desorption process happens. The water flowrate is required to be adjusted to achieve the minimum desorption temperature for the hybrid heat transformer. Meanwhile, electricity yielded by PVT drives the compressor to pressurize the desorbed ammonia to LTS reactor for the sorption process. In the discharge phase, the hot water is used to heat LTS reactor and the ammonia is pressurized to HTS reactor. The sorption heat of HTS is then used for the heat supply with a higher output temperature. One striking contribution is that hybrid heat transformer integrated with solar PVT is quite suitable for the regions with weak solar radiation and limited insolation duration during the winter. This is because heat supply temperature by using solar PVT cannot meet the requirement for domestic heating in most time of winter [40]. The integration of these two technologies increase the output temperature of hot water from solar PVT, which offers an opportunity to solve domestic heating problem by using the renewable energy.

In order to analyse the performance of hybrid resorption-compression heat transformer integrated with solar PVT, experimental sorption characteristics are adopted which have been conducted by a $MnCl_2$-$CaCl_2$-NH_3 sorption system. The details of the system



(a)

(b)

Fig. 14. Hybrid resorption-compression heat transformer with solar PVT (a) in the charging process; (b) in the discharging process.

configuration and working processes can be considered in our previous Ref. [41]. Since the outlet temperature of PVT is the inlet temperature of the resorption heat transformer, the tested results of the resorption system are selected by considering the typical winter conditions and temperature requirements of domestic hot water in Europe i.e. 5 °C cooling temperature, 40 °C heat input temperature and 50–70 °C output temperatures for heat transformer. The mass ratio between reactor and adsorbent is defined as six according to the real situation of sorption system. Fig. 15 indicates the tested global conversion rates of $MnCl_2$-$CaCl_2$ chemisorption working pair with and without the compressor which are the results of the sorption capacities dividing their theoretical maximum values. It is indicated that the tested global conversion rates of basic resorption $MnCl_2$-$CaCl_2$ working pair without using compressor are quite low, which decrease from 0.31 to 0.15 when heat output temperature ranges from 50 °C to 70 °C. This is mainly due to the small pressure potential for the reaction and poor mass transfer. Thus it is not very suitable for a basic resorption system to operate under this conditions in winter since it doesn't lie in the aforementioned range of conversion rate in section 4.2 i.e. 0.7–0.9. Comparably, the global conversion rates of $MnCl_2$-$CaCl_2$ working pair by using the compressor are greatly increased due to the increased pressure potential. The results decrease from 0.93 to 0.704 at 50–70 °C heat output temperatures. Based on the tested sorption characteristics in Fig. 15, heat densities and energy efficiencies of hybrid resorption-compression heat transformer and basic resorption heat transformer system are evaluated, which are shown in Fig. 16. The results clearly demonstrate the advantages of hybrid heat transformer. Besides, the basic resorption heat transformer has a limited heat output temperature i.e. less than 60 °C. This is mainly because thermal capacity of the metal part of the system is relatively high which leads to the great heat loss in the discharging process i.e. the

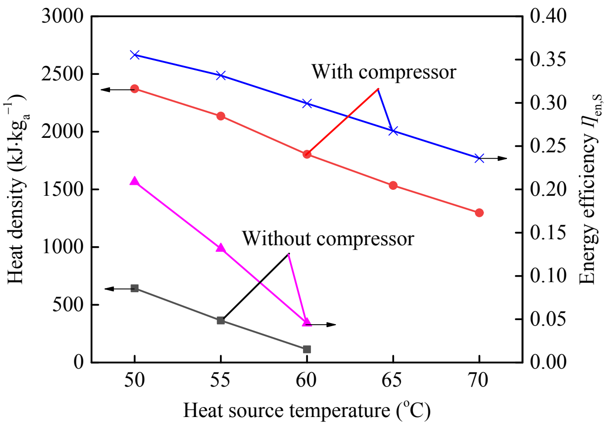
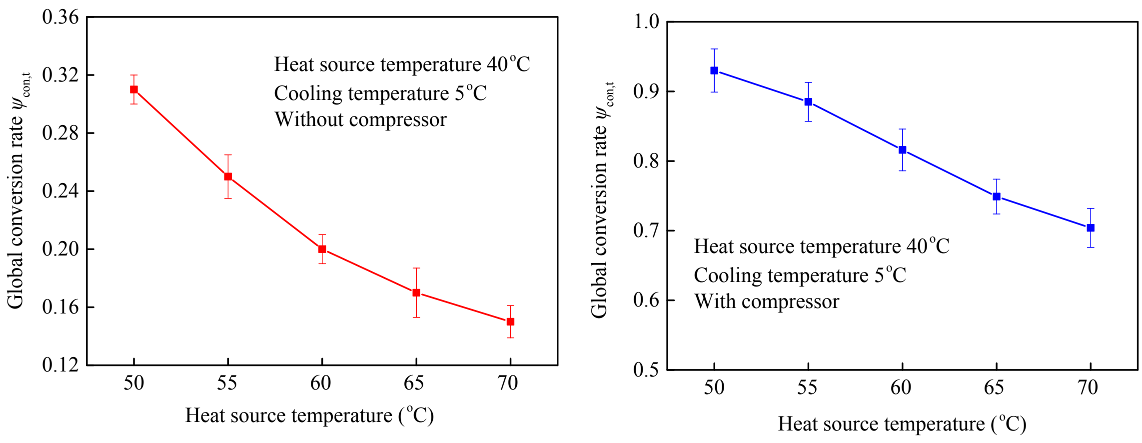


Fig. 16. Heat densities and energy efficiencies of $MnCl_2$-$CaCl_2$ chemisorption working pair with and without compressor.



(a)

(b)

Fig. 15. Global conversion rates of $MnCl_2$-$CaCl_2$ chemisorption working pair (a) without compressor; (b) with compressor.

output heat is significantly consumed by sensible heat of the reactors. It is indicated that heat densities and energy efficiencies of hybrid heat transformer are much higher than those of basic resorption heat transformer. Heat densities of hybrid heat transformer decrease from 2371.8 $kJ{\cdot}kg_a^{-1}$ to 1279.3 $kJ{\cdot}kg_a^{-1}$, which are at least 3.7 times higher than those of the basic resorption type. Besides, energy efficiencies decrease from 0.362 to 0.241 when the output temperature increases from 50 °C to 70 °C. The results are still higher than those of basic resorption type which range from 0.208 to 0.05.

5. Conclusions

In order to have a comprehensive understanding of hybrid resorption-compression heat transformer, its performance is investigated in terms of thermal cycle evaluation, sensitivity analysis and an integrated application with solar photovoltaic thermal collector. The advantage of the hybrid heat transformer is demonstrated when compared with multi-stage resorption heat transformer. Conclusions are yielded as follows:

1. For energy consumption in the charging process, specific work consumption ranges from 25.3 $kJ{\cdot}kg_{am}^{-1}$ to 182.7 $kJ{\cdot}kg_{am}^{-1}$. The specific work increases with the increase of the cooling temperature. In the discharging process, the specific work consumption ranges from 192.4 $kJ{\cdot}kg_{am}^{-1}$ to 203.7 $kJ{\cdot}kg_{am}^{-1}$ when cooling temperature increases from 10 °C to 30 °C. Energy efficiency gradually decreases with the increase of the heat source temperature. When heat source temperature increases from 40 °C to 90 °C, energy and exergy efficiencies of the hybrid heat transformer decrease from 0.429 to 0.403 and from 0.8 to 0.64. Energy efficiency of hybrid heat transformer is almost double higher than that of multi-stage cycle.
2. With the increase of isentropic efficiencies of compressor, energy efficiencies slightly increase from 0.4 to 0.421, while exergy efficiencies increase from 0.597 to 0.791. With global conversion rates from 0.2 to 1, energy efficiencies of hybrid cycle and multi-stage cycle increase from 0.127 to 0.421 and from 0.085 to 0.248. Exergy efficiencies of two sorption heat transformers increase from 0.137 to 0.791 and 0.225 to 0.655. When mass ratios increase from 0 to 8, energy efficiencies of hybrid and multi-stage cycle decrease from 0.421 to 0.196 and 0.238 to 0.106. Exergy efficiencies increase from 0.791 to 0.382 and 0.63 to 0.279.
3. Compared with basic resorption heat transformer, the hybrid resorption-compression type is suitable to be integrated with solar photovoltaic thermal collector for domestic heating application. When heat output temperature ranges from 50 °C to 70 °C, it could ensure that the heat densities are larger than 1000 $kJ{\cdot}kg_{am}^{-1}$ with energy efficiencies higher than 0.24.

Considering the wide use of thermal energy storage and upgrade technologies, the hybrid resorption-compression heat transformer could be a method to solve the problem for energy reuse in various applications. Thermal cycle analysis is the main target of this study to give some general indicators of the hybrid concept. A more detailed analysis will be our future work by considering transient heat and mass transfer, energy loss of components and infinite thermodynamics.

CRediT authorship contribution statement

L. Jiang: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Software, Project administration. **: . R.Q. Wang:** Conceptualization, Investigation, Methodology. **X. Tao: . A.P. Roskilly:** Software, Supervision.

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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