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Analysis on innovative resorption cycle for power and refrigeration cogeneration

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Abstract: A novel resorption cycle with internal heat recovery process is proposed, which is expected to further explore potentials of power and refrigeration cogeneration. Two sets of basic resorption refrigeration cycles are adopted, which are integrated with turbine/expander to realize quasi-continuous output in both half cycles. An improved cogeneration efficiency could be obtained with safety feature. Different ammonia composite sorbents with better heat and mass transfer performance are selected to investigate the overall performance when heat source is in the range from 200°C to 360°C. It is indicated that energy efficiency for power generation is able to reach up to 0.263 at 360°C heat source temperature while refrigeration coefficient of performance could achieve up to 1.31 at 200°C heat source temperature. The optimum total exergy efficiency of novel resorption cogeneration cycle is as high as 0.74 by using working pair of $\text{FeCl}_2\text{-CaCl}_2\text{-BaCl}_2$ at 240°C heat source temperature. Compared with other sorption cycles for power and refrigeration cogeneration at similar heat source temperature, the proposed resorption cycle exhibits the highest exergy efficiency, which is about 30% higher than that of water-ammonia sorption cogeneration cycle, and twice higher than that of basic resorption cogeneration cycle.

Keywords: Resorption; Power generation; Refrigeration; Exergy efficiency

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Nomenclature

COP	Coefficient of performance
c_p	Specific heat capacity ($J \cdot g^{-1} \cdot K^{-1}$)
E	Exergy (kJ)
ENG	Expanded natural graphite
HTS	High temperature sorbent
KCS	Kalina cycle systems
MOF	Metal organic framework
MTS	Middle temperature sorbent
m	Mass (kg)
LTS	Low temperature sorbent
ORC	Organic Rankine Cycle
P	Pressure (Pa)
Q	Heat (kJ)
R	Gas constant ($J \cdot mol^{-1} \cdot K^{-1}$)
T	Temperature ($^{\circ}C$)
W	Power generation (kJ)
Greek letters	
ΔH	Reaction enthalpy of sorbent ($J \cdot mol^{-1}$)
ΔS	Reaction entropy of sorbent ($J \cdot mol^{-1} \cdot K^{-1}$)
η	Efficiency
Subscripts	
a	Ambient
con	Condensation
d	Desorption
ENG	Expanded natural graphite
en	Energy
eq	Equilibrium
ex	Exergy
HTS	High temperature sorbent

i	Theoretical
h	Heat
in	Inlet
MTS	Middle temperature sorbent
LTS	Low temperature sorbent
out	Outlet
R	Reaction
r	Reactor
rec	Recovery
ref	Refrigeraton
s	Sorption
sen	Sensible
salt	Sorbent
tot	Total
w	Power generation

1. Introduction

Low grade heat e.g. solar energy, industrial waste heat, and geothermal energy is ubiquitous, which has attracted burgeoning attentions due to depletion of fossil fuels [1]. Sorption technology has revealed great potentials in harnessing low grade heat by using environmental benign refrigerant, which results in an improved efficiency of energy utilization and CO₂ emission reduction [2]. It is widely acknowledged that sorption cycle could be developed for various functions of air conditioning and freezing [3, 4], heat pump and energy storage [5, 6], desiccant and desalination [7], CO₂ capture and storage [8]. These applications are mainly related with heat and cold loads whereas electricity demand is completely a different scenario. Integration of thermal dynamical cycle with turbine/expander provides enormous opportunities of power generation for low grade heat recovery.

The first attempt of absorption power generation cycle was in the 1950s, which was based on water-ammonia working pairs [9]. About 30 years later, Kalina cycle was proposed for an improved efficiency of power generation [10], and a variety of Kalina cycle systems (KCS) were investigated successively for further exploration, which implied a promising future of this technology [11]. Also

worth noting that a series of demonstration projects around the world have been established based on Kalina cycles, which are driven by geothermal energy, solar thermal energy or industrial waste heat. With some modifications of ammonia-absorption cycle, Goswami cycle was proposed in 1998 for cold and power cogeneration, which was a combination of an ammonia-water absorption cycle and an ammonia-based Rankine cycle [12]. Through accumulative improvement of thermal cycles, higher performance could be gradually realized in terms of efficiency and output.

It is generally admitted that sorption is mainly composed of liquid-gas absorption and solid-gas sorption technology. Similar with ammonia-absorption cycle, ammonia-based chemisorption cycle is also attempted to investigate the extra power generation by combining with an expander, which further extends the spectrum of energy conversion technologies. Innovation of sorption cycle always comes along challenges and opportunities, which trudges through fierce comparison and competition. A typical chemisorption cycle consists of a sorption reactor and a condenser/evaporator. Liquid ammonia inside sorption system will cause safety problems, and system performance is also greatly influenced by condensation temperature [13]. Comparably, another type of chemisorption cycle termed as resorption cycle brings about more advantages. Condenser/evaporator is replaced with a secondary sorption reactor by using another sorbent, which results in an improved refrigeration performance due to the fact that desorption heat is usually higher than evaporation latent heat of ammonia [14]. Resorption cycle often operates at a relatively lower working pressure when compared with typical sorption cycle [15]. This unique characteristic plays a promoting role in integrated system for power generation since pressure difference between inlet and outlet of the expander will be further amplified. Therefore, integrated resorption system for power and refrigeration cogeneration is worth exploring. Similar to absorption cogeneration cycle for power and refrigeration, continuous efforts are made for various sorption chemical and physical cycles in the progress of improving thermal efficiency.

Wang et al. first established a resorption cycle for power and refrigeration cogeneration. It was concluded that the cogeneration system could have a much higher refrigeration performance than that of Goswami cycle [16]. On basis of this resorption cycle, Lu et al. [17] investigated this cogeneration cycle by using mass and heat recovery. Nonetheless, the limited improvement of energy efficiency could be achieved, which was no more than 20%. Hereafter, Bao et al. [18] optimized resorption power generation cycle to gain the maximum power output, and an advanced cycle with optimal arrangement was proposed despite the loss of cooling effect. Except for ammonia-based sorption cycle, Al Mousawi

et al. [19] investigated cogeneration potential of an integrated system by using working pair of metal organic framework (MOF) and water. Later, several sorbents i.e. silica gel, zeolite and MOF were adopted and compared in terms of power and refrigeration performance by incorporating an radial inflow turbine between desorber and condenser [20]. In fact, physisorption systems are relatively difficult for real application since water and methanol-based systems normally work at low pressure, which is lower than atmospheric level or even close to vacuum. For improving stability and continuity of power generation, multi-stage is considered as a good solution for optimization, which is able to be applied to both chemisorption cycles [21] and physisorption cycles [22]. Some lab-scale chemisorption cogeneration systems were established to investigate real experimental performance. The first lab prototype ammonia-based sorption cogeneration machine was established by Bao et al. [23], and results demonstrated that selection of expander for matching sorption system could be a key factor for real electricity output. Our previous work investigated a resorption system for electricity and refrigeration cogeneration. Results indicated that total system efficiency wasn't desirable due to the limitation of cycle efficiency by using a certain kind of working pair [24].

In order to further improve thermal efficiency, a novel resorption cycle for power and refrigeration cogeneration is proposed. Internal heat recovery between two different sorption reactors are first adopted for cogeneration cycle, which is rare reported. Theoretical evaluation of energy and exergy efficiency for power and refrigeration cogeneration is conducted. To avoid swelling and agglomeration, six composite metal halides are employed with expanded natural graphite (ENG), which is commonly used for real sorption reactors.

2. Working principle of resorption cogeneration cycles

For better elaborating resorption cycle with internal heat recovery, a basic resorption cycle for power and refrigeration cogeneration will be first introduced. For chemisorption reaction process, working pressure is determined by working temperature, which can refer to equation 1. When reaction enthalpy and entropy of a chemical working pair are given, P_{eq} could be calculated by a set T_{eq} and vice versa [25].

$$\ln\left(\frac{P_{eq}}{P^0}\right) = -\frac{\Delta H_R}{RT_{eq}} + \frac{\Delta S_R}{R} \quad (1)$$

where R is gas constant, P^0 is the reference pressure i.e.1 Pa, ΔH_R and ΔS_R are reaction enthalpy and

reaction entropy of working pair.

Through transformation of equation 1, equilibrium reaction temperature T_{eq} could be evaluated when equilibrium pressure P_{eq} is ensured, which is expressed as equation 2.

$$T_{eq} = \frac{\Delta H_R}{-R \cdot \ln\left(\frac{P_{eq}}{P^o}\right) + \Delta S_R} \quad (2)$$

Also through transformation of equation 1, equilibrium reaction pressure P_{eq} could be calculated when equilibrium temperature T_{eq} is ensured, which is expressed as equation 3.

$$P_{eq} = P^o \cdot e^{-\frac{\Delta H_R}{RT_{eq}} + \frac{\Delta S_R}{R}} \quad (3)$$

In this paper, two different sorbents are adopted for a resorption cycle for power and refrigeration cogeneration, which are differentiated by their equilibrium reaction temperatures at a same working pressure. Thus one is termed as high temperature sorbent (HTS) while the other is described as low temperature sorbent (LTS) [26].

The concerning schematic is indicated in Fig.1, which is composed of two sorption reactors and an expander. Fig.1a and Fig.1b demonstrate power generation and refrigeration process, respectively.

In the first half cycle, HTS reactor is heated to ensure enough pressure difference as a driving force of chemical reaction. Power is generated till ammonia ends up being sorbed by LTS reactor. In the second half cycle, HTS reactor is cooled by environmental medium while LTS reactor is at refrigeration temperature. Desorption heat of LTS supplies cooling effect. The generated vapour has to be adsorbed by HTS and sorption heat is rejected to the environment.

Thermodynamic working processes of a basic resorption cogeneration cycle are plotted in Fig.2, which could be separated to power generation and refrigeration process as shown in Fig.2a and Fig.2b. The concerning thermodynamic processes of first and second half cycle are consistent with the respective working processes by using the same HTS and LTS in Fig.1a and Fig.1b. Lines that overlap with reaction lines i.e. S/G1 and S/G2 represent the working processes of sorption reactor. Other lines represent the refrigerant. Temperatures and pressures in Fig.2 are correspondingly calculated through equation 2 and 3 by ensuring some parameters e.g. cooling temperature and refrigeration temperature.

In the first half cycle, HTS reactor is heated as E-A and supplied with the heat of $Q_{d,HTS}$ at point A.

Then ammonia vapour is desorbed at $T_{d,HTS}$ and P_H . Ammonia with high pressure and temperature generates power through the expander as A-B. Meanwhile, LTS reactor is heated as D-C through environmental medium at $T_{s,LTS}$ and P_M . Then the expanded ammonia vapour is sorbed by LTS reactor as B-C and release sorption heat $Q_{s,LTS}$. In the second half cycle, HTS reactor is cooled by environmental medium e.g. cooling water from $T_{d,HTS}$ to $T_{s,HTS}$. The process is shown as A-E. Simultaneously, LTS reactor is cooled by another cooling medium with lower temperature range e.g. ethylene glycol from $T_{s,LTS}$ to $T_{d,LTS}$. The process proceeds as C-D. Then the endothermic desorption process of LTS reactor happens and releases ammonia vapour to supply useful cooling power $Q_{d,LTS}$ at point D under constant pressure and temperature i.e. $T_{d,LTS}$ and P_L . Ammonia vapour will be eventually sorbed by HTS reactor as D-E to release sorption heat $Q_{s,HTS}$.

Fig.1. The basic schematic of resorption cogeneration cycle (a) power generation; (b) refrigeration.

Fig.2. The basic principle of resorption cogeneration cycle (a) power generation; (b) refrigeration.

Compared with basic resorption cycle, novel resorption cogeneration cycle with internal heat recovery is shown in Fig.3. The resorption cogeneration cycle is composed of four sorption reactors and two expanders. To accomplish internal heat recovery process, four reactors are filled with three different kinds of sorbents i.e. HTS, middle temperature sorbent (MTS) and LTS to perform two different groups of resorption working pairs. HTS and LTS act as one set of resorption working pair while MTS and LTS act as the other.

Thermodynamic working processes of novel resorption cogeneration cycle with internal heat recovery are plotted as shown in Fig.4. In the first half cycle, HTS and LTS reactor proceed power generation process while MTS and LTS reactor operate refrigeration process, which is similar with a basic resorption cogeneration cycle. In the second half cycle, these two sets of resorption working pairs work alternatively i.e. HTS and LTS reactor proceed refrigeration process while MTS and LTS reactor operate power generation process. Different from basic cycle, heat recovery process also proceeds in the second half cycle. After cooling processes of LTS and HTS reactor as C-D and F-E, sorption process proceeds as D-E. Sorption heat $Q_{s,HTS}$ of HTS reactor is utilized for acting as desorption heat $Q_{d,MTS}$ of MTS reactor, which means no extra heat input in the second half cycle. MTS reactor begins to desorb at point A. The desorbed ammonia is then expanded for power generation as A-B and sorbed by releasing the heat $Q_{s,LTS}$ as B-C. However, internal heat recovery is limited by many factors e.g. working pairs, heating temperature. If internal heat recovery could be realized, power and refrigeration will be supplied twice with inputting the external heat in the first half cycle. Since the same LTS is used for two groups of working pairs, cooling power in both half cycles are supplied in the same level of temperature.

for supplying cooling effect and sorbed by HTS, which is plotted as D-E, D-E' and D-E'' in terms of NiCl_2 , FeCl_2 and MnCl_2 , respectively. Sorption heat of HTS is recovered to heat MTS for desorption. Then power is generated which is shown as A-B. Ammonia will be sorbed by LTS as B-C. One remarkable fact is that HTS with higher equilibrium sorption temperature is required for internal heat recovery process. When desorption temperature of MTS is selected as 100°C , MnCl_2 is not suitable to be selected as HTS due to the fact that its sorption temperature is about 98°C , which is lower than desorption temperature of CaCl_2 . Only part of heat could be recovered, which is not the proposed cycle in this paper. As the proposed cycle mentioned above, sorption temperature of HTS should be higher than desorption temperature of MTS. Under the same external condition, the higher reaction temperature of HTS is generally related with higher reaction heat due to reaction characteristic of chemisorption process. E.g. according to Table 1, desorption temperature of NiCl_2 is higher than that of FeCl_2 , and reaction enthalpy of NiCl_2 is correspondingly higher. This will inevitably result in higher input of the first half cycle, which probably has a negative influence on total cycle efficiency. Thus HTS with relatively lower reaction heat is suitable for the proposed resorption cogeneration cycle in the premise of enough internal heat recovery. Also worth noting that power generation process will have an optimal heat driving temperature. The reason is further elaborated as follows: Power generation process is indicated as A-B when heat driving temperature and cooling temperature are 100°C and 35°C . Cooling water determines sorption pressure of LTS, which is considered as back pressure of expander. It is evident that the expansion limit is point B' due to the fact that it is the intersection of sorption pressure and saturation line of ammonia i.e. line labeled NH_3 . Its driving temperature is higher than 100°C at point A'. If heat driving temperature is even higher, power generation couldn't be further increased since expansion process is assumed to stop when ammonia nearly reaches dew point B''.

Liquid formation should be avoided to cause the damage in the expander. Thus sorption pressure of LTS is first considered for expansion process, and then ammonia saturation line should be regarded as another limit. This rule could also explain the expansion processes in Fig.5b and Fig.5c.

Different LTSs i.e. NH_4Cl and BaCl_2 are selected for comparing their influence on the proposed resorption cogeneration cycle, which are presented in Fig.5b. It is demonstrated that BaCl_2 reveals greater potential in power generation than that of NH_4Cl under the condition of 100°C heat driving temperature and 35°C cooling temperature. With regard to cooling effect, LTS with higher desorption heat will take the advantage, which acts as refrigeration output. E.g. BaCl_2 has the higher cooling output than that of NH_4Cl . Fig.5c demonstrates the influence on the proposed cogeneration cycle in terms of different MTSs i.e. CaCl_2 and SrCl_2 . Power generated by using CaCl_2 is slightly higher than that by using SrCl_2 . Theoretically, MTS has little influence on refrigeration performance i.e. cooling power and COP . This is mainly because no extra heat input is required for MTS in the second half cycle through heat recovery. Thus cooling power is determined by desorption heat of LTS, and COP is determined by desorption heat of LTS and heat input for HTS.

(a)

(b)

(c)

Fig.5. P - T schematic diagram of novel resorption cogeneration cycle by using different sorbents

(a) HTSs; (b) LTSs; (c) MTSs.

3. Analytical methodology of novel resorption cogeneration cycle

As mentioned above, different sorbents are selected in terms of HTS, MTS and LTS.

Thermochemical reaction processes of these sorbents with ammonia can be referred to equations 4-11.

NiCl_2 6/2, FeCl_2 6/2, SrCl_2 8/1, CaCl_2 8/4, BaCl_2 8/0 and NH_4Cl 3/0 are used to simplify descriptions

of thermochemical reaction process of different sorbents. E.g. CaCl_2 8/4 represents the process in

which CaCl_2 ammoniate reacts with ammonia from 4 moles to 8 moles. CaCl_2 4/2 is not presented since it will be eventually reacted with ammonia to 8 moles. Table 1 indicates the main parameters of selected sorbents in terms of equilibrium desorption temperature, reaction enthalpy, reaction entropy and maximum cycle sorption capacity.

Table 1. The main parameters of selected composite sorbents [26].

Sorbent	Desorption temperature (°C)	Reaction enthalpy (J·mol ⁻¹)	Reaction entropy (J·mol ⁻¹ ·K ⁻¹)	Maximum cycle sorption capacity (kg·kg ⁻¹)
NH_4Cl 3/0	48	29433	207.9	0.954
BaCl_2 7/1	56	38250	232.4	0.653
CaCl_2 8/4	87	41013	230.1	0.613
SrCl_2 8/1	96	41431	228.6	0.75
MnCl_2 6/2	152	47416	227.9	0.54
FeCl_2 6/2	186	51266	227.8	0.537
NiCl_2 6/2	259	59217	227.6	0.525

ENG is selected as porous supporting matrix to develop composite sorbents. The developing process could be referred to our previous work [27]. The improved thermal conductivity and permeability are obtained. Thus mass transfer limitation within composite sorbent is able to be ignored at relatively high working pressure without swelling and agglomeration phenomenon.

Heat input of novel resorption cogeneration cycle can be expressed as equation 12:

$$Q_{\text{input}} = Q_{\text{R,HTS}} + Q_{\text{sen}} \quad (12)$$

where Q_{R} is reaction heat of HTS, Q_{sen} is sensible heat.

The sensible part of heat input in equation 12 is composed of ENG, sorbent, ammonia and sorption reactor.

$$Q_{\text{sen}} = [(m \cdot c_p)_{\text{ENG}} + (m \cdot c_p)_{\text{salt}} + (m \cdot c_p)_{\text{NH}_3} + (m \cdot c_p)_{\text{r}}] \cdot (T_{\text{h}} - T_{\text{rec}}) \quad (13)$$

where the first term in the right side of equation 13 is sensible heat consumed by ENG, the second and third term are sensible heat consumed by sorbent and ammonia, respectively. The fourth term is sensible heat consumed by metal part of sorption reactor. T_{h} is heat input temperature for HTS in the first half cycle. T_{rec} is heat recovery temperature in the second half cycle, which is determined by sorption temperature of HTS and desorption temperature of MTS.

Heat exergy input could be expressed as equation 14:

$$E_{\text{input}} = (1 - T_{\text{a}} / T_{\text{h}}) \cdot Q_{\text{input}} \quad (14)$$

where T_{a} is ambient temperature.

The power is generated, which could be expressed as equation 15:

$$W = E_{\text{w}} = m_{\text{NH}_3} \cdot (h_{\text{out}} - h_{\text{in}}) \quad (15)$$

where h_{out} and h_{in} are the expander outlet and inlet enthalpy of ammonia vapour.

Refrigeration could be expressed as equation 16:

$$Q_{\text{ref}} = Q_{\text{R,LTS}}' - Q_{\text{sen}}' \quad (16)$$

where $Q_{\text{R,LTS}}'$ is reaction heat of LTS, Q_{sen}' is sensible heat.

The sensible part of refrigeration could be expressed as equation 17, which are composed of ENG, sorbent, ammonia and sorption reactor.

$$Q_{\text{sen}}' = [(m \cdot c_p)_{\text{ENG}} + (m \cdot c_p)_{\text{salt}} + (m \cdot c_p)_{\text{NH}_3} + (m \cdot c_p)_{\text{r}}] \cdot (T_{\text{a}} - T_{\text{ref}}) \quad (17)$$

where the first term in the right side of equation 17 is sensible heat consumed by ENG, the second and third term are sensible heat consumed by sorbent and ammonia, respectively. The fourth term is

sensible heat consumed by metal part of sorption reactor. T_{ref} is refrigeration temperature.

Refrigeration exergy could be expressed as equation 18:

$$E_{\text{ref}} = (T_a / T_{\text{ref}} - 1) \cdot Q_{\text{ref}} \quad (18)$$

Energy efficiency of power and refrigeration could be expressed as equation 19 and 20:

$$\eta_{\text{en,w}} = (W_1 + W_2) / Q_{\text{input}} \quad (19)$$

$$COP = (Q_{\text{ref1}} + Q_{\text{ref2}}) / Q_{\text{input}} \quad (20)$$

where the subscript 1 and 2 denote the first half cycle and the second half cycle, respectively.

Exergy efficiency of power and refrigeration could be expressed as equation 21 and 22:

$$\eta_{\text{ex,w}} = (E_{\text{w1}} + E_{\text{w2}}) / E_{\text{input}} \quad (21)$$

$$\eta_{\text{ex,ref}} = (E_{\text{ref1}} + E_{\text{ref2}}) / E_{\text{input}} \quad (22)$$

Total exergy efficiency of novel resorption cycle for power and refrigeration cogeneration could be expressed as equation 23:

$$\eta_{\text{ex,tot}} = \eta_{\text{ex,w}} + \eta_{\text{ex,ref}} \quad (23)$$

4. Results and discussions

4.1 Ideal performance

Ideal performance is first evaluated, which points out theoretical limitation of novel resorption cycle for power and refrigeration cogeneration. Both ENG and metal of sorption reactor will not be considered in the part. Global conversion rate is used for investigation, which is defined as the percentage of composite sorbent that reacts with the refrigerant. Fig.6 shows ideal COP of novel resorption cogeneration cycle with regard to different groups of working pairs. It is indicated that resorption cogeneration cycle enjoys a relatively high COP due to internal heat recovery between HTS and MTS, which results in double output with heat input once. The highest COP_1 is able to reach 1.5

and the results of other three working pairs are higher than or equal to 1 when global conversion rate is

1. By using BaCl_2 as LTS, COP_i could still reach 1 when global conversion rate decreases to 0.8. Also worth noting that the proposed resorption cogeneration cycle by using FeCl_2 as HTS has a higher COP_i than that employing NiCl_2 due to the lower reaction enthalpy of the former sorbent. MTS has no influence on COP_i , which is not indicated in Fig.6.

Fig.6. COP_i of novel resorption cogeneration cycle vs. different global conversion rates.

Since power output of novel resorption cogeneration cycle is quite relevant to heat source temperature and working pairs, the results will be variable in terms of different external conditions. Thus specific work output for power generation is used to initially evaluate the performance, which refers to 1 kg of ammonia by enthalpy difference. Specific work output could be related with one half cycle i.e. either first or second half working cycle, which is only determined by LTS when expander inlet pressure is given. Fig.7a and Fig.7b indicate specific work output by using NH_4Cl and BaCl_2 as LTS, respectively. BaCl_2 has a higher specific work output than that of NH_4Cl . This is mainly because NH_4Cl has a higher constraint pressure i.e. 5.5 bar whereas BaCl_2 has a lower value i.e. 3.5 bar under

the condition of 30°C environmental temperature, which acts as a back pressure of expander. Thus enthalpy difference between inlet and outlet of the expander by using BaCl_2 will be larger than that by using NH_4Cl as LTS.

Fig.7. Specific power output of novel resorption cogeneration cycle by using different LTSs

(a) NH_4Cl ; (b) BaCl_2 .

4.2 Separated and overall performance analysis

In general, global conversion rate is eventually bound to reach 1 with sufficient reaction duration when the constraining temperature/pressure is away from equilibrium conditions. Nevertheless, it is always difficult to reach 1 with finite reaction duration in real application due to the fact that reaction rate is greatly influenced by heat and mass transfer performance of sorbent. In this paper, global conversion rate is assumed as 80% since the extra 20% of global conversion rate extends the cycle time considerably. The required mass of different sorbents are shown in Table 2, and the metal part of sorption reactor is not analyzed in this part, which will be further illustrated in next section.

Fig.8 indicates COP of the proposed resorption cycle for power and refrigeration cogeneration

under the condition of 10°C refrigeration temperature. Cycle performance by using different HTSs are compared in Fig.8a and Fig.8b, respectively. It is demonstrated that *COP* of the cycle decreases with the increase of heat source temperature due to excessive sensible heat input. With regard to the minimum required driving temperature, heat source temperature ranges from 200°C to 300°C and from 260°C to 360°C in terms of FeCl₂ and NiCl₂. It is indicated that FeCl₂ has a higher *COP* than NiCl₂ due to its lower reaction enthalpy as heat input whereas BaCl₂ shows a better performance than NH₄Cl owing to its higher reaction enthalpy as cold output. Also performance by using different MTSs i.e. CaCl₂ and SrCl₂ are almost the same for novel resorption cogeneration cycle. This is mainly because heat input is determined by heat source temperature and desorption heat of HTS. Refrigeration output is determined by refrigeration temperature and desorption heat of LTS. Influence of MTS on *COP* is almost negligible as long as internal heat recovery could be satisfied. Thus no difference by using various MTSs is presented in Fig.8a and Fig.8b. By using FeCl₂-BaCl₂ working pair, the highest *COP* could reach 1.31 under the condition of 200°C heat source temperature. Even the lowest *COP* still reaches 0.82 by using NiCl₂-NH₄Cl at 360°C heat source temperature.

Exergy efficiency of refrigeration is evaluated by using different HTSs i.e. FeCl₂ and NiCl₂, which is indicated in Fig.9a and Fig.9b. Results show that exergy efficiency also decreases with the increase of heat source temperature, which has a larger decline than that of *COP* since refrigeration exergy is relatively low. It is demonstrated that the highest exergy efficiency of refrigeration could reach 0.259 by using FeCl₂-BaCl₂ at 200°C heat source temperature. For different resorption working pairs, exergy efficiency of refrigeration ranges between 0.111 and 0.259 when heat source temperature ranges from 200°C to 360°C.

Table 2. The required mass of sorbents with regard to 1 kg of ammonia.

Sorbent	The required mass
NH_4Cl	$1.31 \text{ kg}_{\text{salt}} \cdot \text{kg}_{\text{NH}_3}^{-1}$
BaCl_2	$1.91 \text{ kg}_{\text{salt}} \cdot \text{kg}_{\text{NH}_3}^{-1}$
CaCl_2	$1.66 \text{ kg}_{\text{salt}} \cdot \text{kg}_{\text{NH}_3}^{-1}$
SrCl_2	$1.91 \text{ kg}_{\text{salt}} \cdot \text{kg}_{\text{NH}_3}^{-1}$
FeCl_2	$2.33 \text{ kg}_{\text{salt}} \cdot \text{kg}_{\text{NH}_3}^{-1}$
NiCl_2	$2.38 \text{ kg}_{\text{salt}} \cdot \text{kg}_{\text{NH}_3}^{-1}$

Fig.8. *COP* of novel resorption cogeneration cycle vs. different heat source temperatures

(a) FeCl_2 as HTS; (b) NiCl_2 as HTS.

Fig.9. Exergy efficiency of novel resorption cogeneration cycle vs. different heat source temperatures

(a) FeCl_2 as HTS; (b) NiCl_2 as HTS.

Fig.10 presents energy efficiency for power generation in terms of different heat source temperatures. Different from refrigeration performance, power generation is also related with MTS with regard to power output in a second half cycle. Thus CaCl_2 and SrCl_2 need to be considered separately. Result indicates that energy efficiency increases with the increase of heat source temperature. This could be attributed to the fact that the higher heat source temperature results in more power output when compared with heat input. The highest power generation efficiency is as high as 0.263 by using $\text{NiCl}_2\text{-CaCl}_2\text{-BaCl}_2$ at 360°C heat source temperature due to the lower heat input of NiCl_2 and higher total power output of $\text{NiCl}_2\text{-BaCl}_2$ and $\text{CaCl}_2\text{-BaCl}_2$. For similar external heating conditions i.e. 260-300°C heat source temperature and ambient temperature, FeCl_2 , CaCl_2 and BaCl_2 are desirable selections among HTSs, MTSs and LTSs to obtain the relatively high power generation performance, which conforms to initial analysis in Fig.5. For different working pairs, energy efficiency of power generation is in the range between 0.113 and 0.263.

Exergy efficiency for power generation is also assessed, which is shown in Fig.11. Results show that exergy efficiency always increases with the increase of heat source temperature by using NiCl_2 as HTS. This is mainly because the increment of power is larger than the increment of exergy input in this temperature range of heat source. Considering FeCl_2 as HTS, the increment of power is larger than the increment of heat exergy input when heat source temperature is low, which results in the increase of exergy efficiency for power generation. Then it tends to be constant due to the fact that the increment of heat exergy input is balanced with the increment of power. It is indicated that LTS with the lower equilibrium reaction pressure and HTS with the higher equilibrium reaction pressure at a given temperature enjoy better performance. The highest exergy efficiency for power generation could reach 0.538 by using $\text{FeCl}_2\text{-CaCl}_2\text{-BaCl}_2$ with heat source temperature of 300°C. This is determined by total

power output of both half cycles and heat exergy input of FeCl_2 . Higher total power output and lower heat exergy input leads to the higher exergy efficiency for power generation. For different working pairs, exergy efficiency of power generation is in the range between 0.274 and 0.538.

Fig.10. Energy efficiency for power generation of novel resorption cogeneration cycle vs. different heat source temperatures (a) FeCl_2 as HTS; (b) NiCl_2 as HTS.

Fig.11. Exergy efficiency for power generation of novel resorption cogeneration cycle vs. different heat source temperatures (a) FeCl_2 as HTS; (b) NiCl_2 as HTS.

In regard of reasonable evaluating the overall performance of novel resorption cogeneration cycle, energy efficiency will not be analyzed since power generation and refrigeration have a distinct energy grade. Comparably, total exergy efficiency for power and refrigeration cogeneration is adopted for further elaboration, which is shown in Fig.12. The variation trends of total exergy efficiency is similar with that of exergy efficiency of power generation, which indicates that power generation still takes a leading role in total exergy efficiency. For power and refrigeration cogeneration, the maximum exergy efficiency is as high as 0.74 by using working pair of $\text{FeCl}_2\text{-CaCl}_2\text{-BaCl}_2$ at 240°C heat source temperature. Total exergy efficiency ranges from 0.415 to 0.74 in terms of different heat source temperatures and working pairs.

Fig.12. Total exergy efficiency of novel resorption cogeneration cycle vs. different heat source temperatures (a) FeCl_2 as HTS; (b) NiCl_2 as HTS.

4.3 Influence of metal thermal capacity

This section aims to investigate the influence of metal part on the performance of resorption cycle for power and refrigeration cogeneration. Mass ratio is usually used to evaluate the performance in real

application, which is defined as the specific value between mass of sorption reactor and composite sorbent i.e. mass of metal part divided by total mass of salts and ENG. Total exergy efficiency of proposed resorption cogeneration cycle in terms of different mass ratios is presented in Fig.13. Fig.13a and Fig.13b demonstrate the performance by using different HTSs i.e. FeCl_2 and NiCl_2 . 200°C and 260°C are exemplified for further illustration since similar trends could be obtained at other heat source temperatures. It is indicated that mass ratio has a remarkable influence on system performance due to the increased heat input of HTS reactor and extra heat consumption of LTS reactor. With the increased heat exergy input of metal part, total exergy efficiency decreases with the increase of mass ratio. When mass ratio increases from 0 to 10, total exergy efficiency of novel resorption cogeneration cycle varies from 0.719 to 0.53 by using $\text{FeCl}_2\text{-CaCl}_2\text{-BaCl}_2$, which is decreased by 26.3%. For different working pairs, the decline is in the range between 26% and 29.4%. In real sorption systems, mass ratio between sorption reactor and sorbent is determined by various factors e.g. sorption reactor type, compression method, manufacturing technology etc. [28]. Mass ratio of 3 is a limit at the moment that can be achieved through overall improvements. Under this scenario, total exergy efficiency of resorption cogeneration cycle is decreased by less than 10% when compared with theoretical performance i.e. mass ratio is 0. When mass ratio varies from 3 to 10, exergy efficiency is decreased by less than 30%. In real application, it is desirable to reduce mass ratio between metal and sorbent through optimal design and material improvement. Thus a higher thermal efficiency of power and refrigeration cogeneration could be ensured.

Fig.13. Total exergy efficiency of novel resorption cogeneration cycle vs. different mass ratios between metal part of reactor and sorbent. (a) FeCl_2 as HTS; (b) NiCl_2 as HTS.

As mentioned above, one striking fact is that internal heat recovery between HTS and MTS reactor is a prerequisite to ensure this proposed resorption cogeneration cycle with high thermal efficiency. Thus heat released by HTS reactor during the sorption process is required to be higher than that heat input in the desorption process of MTS reactor.

Heat released by HTS reactor and heat consumed by MTS reactor could be expressed by equation 24 and 25, which are used for further evaluation. Since internal heat recovery happens between HTS and MTS reactor, both reaction heat $Q_{R,HTS}$ and sensible heat of HTS could be recovered. The sensible heat is recovered when HTS is cooled from heat input temperature T_h to heat recovery temperature T_{rec} . Similarly, the sensible heat of MTS is obtained when MTS is heated from sorption temperature T_a to heat recovery temperature T_{rec} . Thus the sensible heat recovery is mainly determined by these parameters i.e. T_{rec} , T_a and T_h .

$$Q_{s,HTS} = Q_{R,HTS} + [(m \cdot c_p)_{ENG} + (m \cdot c_p)_{salt} + (m \cdot c_p)_{NH_3} + (m \cdot c_p)_r] \cdot (T_h - T_{rec}) \quad (24)$$

$$Q_{d,MTS} = Q_{R,MTS} + [(m \cdot c_p)_{ENG} + (m \cdot c_p)_{salt} + (m \cdot c_p)_{NH_3} + (m \cdot c_p)_r] \cdot (T_{rec} - T_a) \quad (25)$$

Fig.14 presents heat production of HTS reactor and heat consumption of MTS reactor with regard to different mass ratios between metal part of reactor and sorbent. It is indicated that heat production and heat consumption by using FeCl_2 - CaCl_2 and NiCl_2 - SrCl_2 increase with the increase of mass ratio. Heat production is higher than heat consumption, which reveals that internal heat recovery could be ensured. Also worth noting that heat difference between heat production of FeCl_2 and heat consumption of CaCl_2 is relatively smaller than that between NiCl_2 and SrCl_2 due to the higher reaction heat of NiCl_2 . This reveals that novel resorption cogeneration cycle is easier to be achieved by using NiCl_2 than FeCl_2 as HTS in regardless of cycle efficiency. Similar results could be applied for other two working pairs of FeCl_2 - SrCl_2 and NiCl_2 - CaCl_2 . For real application, heat insulation from other heat sink also needs to be well maintained to ensure a high efficiency of resorption cogeneration system since heat loss plays a negative role for low grade heat utilization. The proposed resorption cycle is not suitable to be applied for long term heat recovery, but this concept still saves part of heat input for MTS reactor. Thus total efficiency could have a little improvement

Fig.14. Heat production and heat consumption vs. different mass ratios between metal part of reactor and sorbent. (a) FeCl_2 - CaCl_2 ; (b) NiCl_2 - SrCl_2 .

4.4 Comparison among various sorption cogeneration technologies

Several sorption technologies are selected to compare cogeneration performance of proposed resorption cycle with other cycles in terms of different working pairs and heat source temperatures, which are indicated in Table 3. Water and ammonia are two main working fluids to achieve power and refrigeration cogeneration. Water-based sorption technologies are widely applied in the field of air conditioner. Silica gel-water sorption chiller is a good example, which is gradually commercialized in recent decades. However, it is quite difficult to integrate sorption chiller with a suitable turbine/expander in real application due to the limited pressure difference between negative pressure and that close to vacuum. It is evident that volume of this expander could be large due to its expansion ratio. No power output could be obtained if vacuum is not well maintained. Also water-based sorption system could not be used for freezing demands, which reflects that ammonia-based sorption system takes more advantages. Controversy about ammonia-based sorption system is about safety problem. But it could be overcome through good maintenance and inspection as quite a lot of ammonia power plants have been well operated. Thus ammonia working pairs are more suitable for real sorption cogeneration systems.

In regard of heat source temperature, it is worth noting that water-based sorption system for power and refrigeration cogeneration has a relatively low heat driving temperature due to the characteristic of sorbate e.g. silica gel-water working pairs could not work at a temperature higher than 120°C. Comparably ammonia-based sorption and resorption cogeneration system have a high heat driving temperature, which enjoy a wide range from 100°C to 450°C by using different working pairs. For similar temperature of heat utilization, exergy efficiency of novel resorption cogeneration cycle proposed in this study shows the highest value, which is about 30% higher than that of water-ammonia

sorption system, and twice higher than that of basic resorption cogeneration system.

Table 3. Selected sorption technologies used for power and refrigeration cogeneration.

Author	Working pair	Heat source temperature (°C)	Performance description
AL-Mousawi et al. [19]	Silica gel, Zeolite, MOF/water	80-160	Overall energy efficiency is increased by up to 11%, and the maximum energy efficiency is 67%.
AL-Mousawi et al. [20]	Silica gel, Zeolite, MOF/water	80-160	Overall energy efficiency is increased by up to 11%, and the maximum energy efficiency is 69%.
AL-Mousawi et al. [22]	Silica gel, Zeolite, MOF/water	80-160	The maximum exergy efficiency is 54% by using silica-gel at 80°C.
Hasan et al. [29]	Water/ammonia	57-197	Maximum exergy efficiency of 65.8%
Zheng et al. [30]	Water/ammonia	350	Overall energy efficiency is 24.2%, and exergy efficiency is 37.3%
Vijayaraghavan et al. [31]	Water/ammonia	87-207	Energy efficiency is 25% higher than the basic cogeneration cycle
Zhang et al. [32]	Water/ammonia	450	Cycle energy and exergy efficiency are 27.7% and 55.7%
Liu et al. [33]	Water/ammonia	450	Exergy efficiency is 58%, which is increased by 22.3%
Wang et al. [16]	8 different salts/ammonia	100-400	The highest exergy efficiency is 69% (40-60% higher than Goswami cycle)
Bao et al. [23]	CaCl ₂ &AC /ammonia	150-230	COP is 0.2 and maximum generated power is 490 W.
Bao et al. [34]	MnCl ₂ /ammonia	100-120	The maximum exergy efficiency is 0.62
Jiang et al. [35]	5 different salts/ammonia	100-400	Electrical efficiency is 15.8%, COP of 0.691 and exergy efficiency of 82%
Jiang et al. [36]	MnCl ₂ -CaCl ₂ /ammonia	130	Energy and exergy efficiency range from 31.6% to 37.6% and from 0.402 to 0.391
Jiang et al. [24]	MnCl ₂ -CaCl ₂ /ammonia	100-200	The total energy and exergy efficiency are increased from 0.293 to 0.417 and from 0.12 to 0.16.
Lu et al. [17]	12 different salts/ammonia	100-300	COP is increased by 38%; electricity efficiency is improved from 8% to 12% and exergy efficiency reached 41%
Present study	6 different salts/ammonia	200-360	The maximum exergy efficiency is as high as 0.74

In order to further clarify the originality of this paper, resorption power and refrigeration cogeneration cycle with internal heat recovery is compared with our concerning previous studies, which are demonstrated in Table 4. The main differences lie in sorbent, heat recovery method and evaluation of metal part, which will result in various possible cycle performance. Among them, internal heat recovery is the key methodology for the proposed resorption cogeneration cycle, which is necessary to further elaborate as follow. It is extensively recognized that performance of sorption cycle could be improved through advanced thermal cycles, e.g. as heat and mass recovery cycle [37], cascaded cycle [38], two-stage cycle [39], thermal wave cycle [40], etc. These cycles are widely investigated by using physical working pairs e.g. silica gel-water and even adopted for real application. Nonetheless, chemisorption cycle has similarities but more differences due to monovariant characteristic rather than dual variant properties. Thus the performance of physical sorption cycle cannot be analogized to chemical sorption cycle even if a similar internal heat recovery has been analyzed. Also the above comparison demonstrates that water-based sorption technology is not suitable for power and refrigeration cogeneration. As shown in Table 4, previous researches of chemisorption cogeneration mainly concentrates on heat recovery of two identical reactors i.e. same working pair, which could only recover part of heat input. Comparably, it is the first time for resorption cogeneration cycle to recover internal heat between different working pairs, which reveals the possible potentials and obtains the highest cycle efficiency.

Table 4. Comparison among previous studies of chemisorption cogeneration.

Research method	Sorbents	Description and novelty	Ref.
Experiment	CaCl ₂ &AC	Sorption experimental rig without heat and mass recovery; Use composite sorbent	[23]

Experiment	MnCl ₂ -CaCl ₂ &ENG	Resorption experimental rig without heat and mass recovery; Use composite sorbent; Modify scroll expander	[24]
Performance analysis	8 metal halides	First to propose chemisorption cogeneration cycle; heat recovery between two identical reactors	[16]
Performance analysis	MnCl ₂ &ENG	Sorption system prediction and optimization by using dynamic model	[34]
Performance analysis	12 metal halides	Resorption cogeneration cycle with heat and mass recovery between two identical reactors	[17]
Performance analysis	8 metal halides	Sorption system prediction by using experimental kinetic results of different resorption working pairs	[41]
Performance analysis	6 metal halides&ENG	Resorption cogeneration cycle with heat recovery between two cascaded reactors; Evaluation of metal capacity; Higher energy and exergy efficiency	Present study

5. Conclusions

A novel resorption cogeneration cycle is proposed, which indicates an improved power generation and refrigeration performance through effective internal heat recovery between HTS and MTS reactor. Composite sorbents with ENG as matrix are adopted for cycle analysis. Power generation and refrigeration performance are separately and generally evaluated. Conclusions are yielded as follows:

- (1) It is indicated that novel sorption cogeneration system enjoys a relatively high ideal COP due to internal heat recovery between HTS and MTS. The highest COP_i is able to reach 1.5, and COP_i by using other three working pairs is higher than or equal to 1 when global conversion rate is 1. Also worth noting that novel resorption cogeneration cycle by using FeCl₂ as HTS has a higher COP_i than that employing NiCl₂.
- (2) COP of novel resorption cogeneration cycle and its exergy efficiency of refrigeration decreases with the increase of heat source temperature. FeCl₂ has a higher COP than NiCl₂ whereas BaCl₂ shows a better performance than NH₄Cl. By using FeCl₂-BaCl₂, the highest COP could reach 1.31. The highest exergy efficiency of refrigeration could reach 0.259 by using FeCl₂-CaCl₂-BaCl₂. For different working pairs, exergy efficiency of refrigeration ranges between 0.111 and 0.259.

- (3) The highest power generation efficiency is as high as 0.263 by using $\text{NiCl}_2\text{-CaCl}_2\text{-BaCl}_2$ at 360°C heat source temperature. Exergy efficiency for power generation increases with the increase of heat source temperature by using NiCl_2 as HTS. Considering FeCl_2 as HTS, exergy efficiency increases first and then decreases with the increment of heat source temperature. Energy and exergy efficiency of power generation range from 0.113 to 0.263 and from 0.274 to 0.538, respectively. Power generation takes a leading role in total exergy efficiency. For power and refrigeration cogeneration, the maximum total exergy efficiency is as high as 0.74 by using working pair of $\text{FeCl}_2\text{-CaCl}_2\text{-BaCl}_2$ at 240°C heat source temperature. Total exergy efficiency ranges from 0.415 to 0.74.
- (4) Water-based sorption cogeneration system has a relatively low heat driving temperature which is usually lower than 160°C . Comparably, ammonia-based sorption cogeneration system has a wide range between 100°C and 450°C . For similar heat source temperature, exergy efficiency of this proposed novel resorption cogeneration cycle is about 30% higher than that of water-ammonia sorption system. Compared with heat recovery between two identical reactors, the proposed cogeneration cycle recovers internal heat between different working pairs, which further explores the possible potentials of cycle efficiency.

With the potentially wide use of energy conversion technology for low grade heat utilization, novel resorption cycle for power and refrigeration cogeneration could be considered as a method to meet the requirement of electricity and refrigeration. One possible application is to recover the waste heat from power plant and industrial factory, which acts as a sub-cycle after Rankine cycle. Cooling power is used for office building whereas electricity could be applied for auxiliary equipment e.g. water pump, cooling fan, heater, etc. Due to its high exergy efficiency for power and refrigeration

cogeneration, it could be another good choice when comparing with cascading cogeneration cycle by using (Organic Rankine Cycle) ORC and absorption technology.

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References

- [1] Ammar Y, Joyce S, Norman R, Wang Y, Roskilly AP. Low grade thermal energy sources and uses from the process industry in the UK. *Applied Energy*. 2012;89(1):3-20.
- [2] Roskilly AP, Taylor PC, Yan J. Energy storage systems for a low carbon future – in need of an integrated approach. *Applied Energy*. 2015;137:463-6.
- [3] Tokarev MM, Gordeeva LG, Grekova AD, Aristov YI. Adsorption cycle “heat from cold” for upgrading the ambient heat: The testing a lab-scale prototype with the composite sorbent CaClBr/silica. *Applied Energy*. 2018;211:136-45.
- [4] Freni A, Maggio G, Sapienza A, Frazzica A, Restuccia G, Vasta S. Comparative analysis of promising adsorbent/adsorbate pairs for adsorptive heat pumping, air conditioning and refrigeration. *Applied Thermal Engineering*. 2016;104:85-95.
- [5] Zhu FQ, Jiang L, Wang LW, Wang RZ. Experimental investigation on a $\text{MnCl}_2\text{-CaCl}_2\text{-NH}_3$ resorption system for heat and refrigeration cogeneration. *Applied Energy*. 2016;181:29-37.
- [6] Aydin D, Casey SP, Chen X, Riffat S. Numerical and experimental analysis of a novel heat pump driven sorption storage heater. *Applied Energy*. 2018;211:954-74.
- [7] Jagirdar M, Lee PS. Mathematical modeling and performance evaluation of a desiccant coated

fin-tube heat exchanger. *Applied Energy*. 2018;212:401-15.

[8] Zhao R, Deng S, Liu Y, Zhao Q, He J, Zhao L. Carbon pump: Fundamental theory and applications. *Energy*. 2017;119:1131-43.

[9] Maloney J, Robertson R. Thermodynamic study of heat power cycles. Oak Ridge National Laboratory Report. 1953:CF-53-8-43.

[10] Kalina AI. Combined Cycle and Waste Heat Recovery Power Systems Based on a Novel Thermodynamic Energy Cycle Utilizing Low-Temperature Heat for Power Generation. 1983(79368):V001T02A3.

[11] Wang E, Yu Z. A numerical analysis of a composition-adjustable Kalina cycle power plant for power generation from low-temperature geothermal sources. *Applied Energy*. 2016;180(Supplement C):834-48.

[12] DY G. Solar thermal power-status of technologies and opportunities for research. Proceedings of the second ISHNT-ASME heat & mass transfer conference. Suratkal, India1995. p. 57-60.

[13] Xu X, Li Y, Yang S, Chen G. A review of fishing vessel refrigeration systems driven by exhaust heat from engines. *Applied Energy*. 2017;203(Supplement C):657-76.

[14] Jiang L, Roskilly AP, Wang RZ, Wang LW, Lu YJ. Analysis on innovative modular sorption and resorption thermal cell for cold and heat cogeneration. *Applied Energy*. 2017;204:767-79.

[15] Vasiliev LL, Mishkinis DA, Antukh AA, Kulakov AG, Vasiliev LL. Resorption heat pump. *Applied Thermal Engineering*. 2004;24(13):1893-903.

[16] Wang L, Ziegler F, Roskilly AP, Wang R, Wang Y. A resorption cycle for the cogeneration of electricity and refrigeration. *Applied Energy*. 2013;106:56-64.

[17] Lu Y, Wang Y, Bao H, Yuan Y, Wang L, Roskilly AP. Analysis of an optimal resorption

cogeneration using mass and heat recovery processes. *Applied Energy*. 2015;160(Supplement C):892-901.

[18] Bao H, Ma Z, Roskilly AP. An optimised chemisorption cycle for power generation using low grade heat. *Applied Energy*. 2017;186(Part 3):251-61.

[19] Al-Mousawi FN, Al-Dadah R, Mahmoud S. Low grade heat driven adsorption system for cooling and power generation using advanced adsorbent materials. *Energy Conversion and Management*. 2016;126:373-84.

[20] Al-Mousawi FN, Al-Dadah R, Mahmoud S. Low grade heat driven adsorption system for cooling and power generation with small-scale radial inflow turbine. *Applied Energy*. 2016;183:1302-16.

[21] Bao H, Ma Z, Roskilly AP. A chemisorption power generation cycle with multi-stage expansion driven by low grade heat. *Energy Conversion and Management*. 2017;150:956-65.

[22] Al-Mousawi FN, Al-Dadah R, Mahmoud S. Different bed configurations and time ratios: Performance analysis of low-grade heat driven adsorption system for cooling and electricity. *Energy Conversion and Management*. 2017;148:1028-40.

[23] Bao H, Wang Y, Charalambous C, Lu Z, Wang L, Wang R, et al. Chemisorption cooling and electric power cogeneration system driven by low grade heat. *Energy*. 2014;72:590-8.

[24] Jiang L, Wang LW, Liu CZ, Wang RZ. Experimental study on a resorption system for power and refrigeration cogeneration. *Energy*. 2016;97:182-90.

[25] Scapino L, Zondag HA, Van Bael J, Diriken J, Rindt CCM. Sorption heat storage for long-term low-temperature applications: A review on the advancements at material and prototype scale. *Applied Energy*. 2017;190:920-48.

[26] Jiang L, Wang LW, Zhou ZS, Zhu FQ, Wang RZ. Investigation on non-equilibrium performance of

composite adsorbent for resorption refrigeration. *Energy Conversion and Management*. 2016;119:67-74.

[27] Jiang L, Wang LW, Jin ZQ, Tian B, Wang RZ. Permeability and thermal conductivity of compact adsorbent of salts for sorption refrigeration. *Journal of heat transfer ASME*. 2012;134:104503-6.

[28] Jiang L, Lu YJ, Tang K, Wang YD, Wang R, Roskilly AP, et al. Investigation on heat and mass transfer performance of novel composite strontium chloride for sorption reactors. *Applied Thermal Engineering*. 2017;121(Supplement C):410-8.

[29] Hasan AA, Goswami DY, Vijayaraghavan S. First and second law analysis of a new power and refrigeration thermodynamic cycle using a solar heat source. *Solar Energy*. 2002;73(5):385-93.

[30] Zheng D, Chen B, Qi Y, Jin H. Thermodynamic analysis of a novel absorption power/cooling combined-cycle. *Applied Energy*. 2006;83(4):311-23.

[31] Vijayaraghavan S, Goswami DY. A combined power and cooling cycle modified to improve resource utilization efficiency using a distillation stage. *Energy*. 2006;31(8):1177-96.

[32] Zhang N, Lior N. Development of a Novel Combined Absorption Cycle for Power Generation and Refrigeration. *Journal of Energy Resources Technology*. 2006;129(3):254-65.

[33] Liu M, Zhang N. Proposal and analysis of a novel ammonia–water cycle for power and refrigeration cogeneration. *Energy*. 2007;32(6):961-70.

[34] Bao H, Wang Y, Roskilly AP. Modelling of a chemisorption refrigeration and power cogeneration system. *Applied Energy*. 2014;119:351-62.

[35] Jiang L, Wang LW, Roskilly AP, Wang RZ. Design and performance analysis of a resorption cogeneration system. *International Journal of Low-Carbon Technologies*. 2013;8(suppl_1):i85-i91.

[36] Jiang L, Wang LW, Zhang XF, Liu CZ, Wang RZ. Performance prediction on a resorption

cogeneration cycle for power and refrigeration with energy storage. *Renewable Energy*. 2015;83:1250-9.

[37] Santori G, Sapienza A, Freni A. A dynamic multi-level model for adsorptive solar cooling. *Renewable Energy*. 2012;43:301-12.

[38] Choudhury B, Saha BB, Chatterjee PK, Sarkar JP. An overview of developments in adsorption refrigeration systems towards a sustainable way of cooling. *Applied Energy*. 2013;104:554-67.

[39] Mitra S, Thu K, Saha BB, Dutta P. Performance evaluation and determination of minimum desorption temperature of a two-stage air cooled silica gel/water adsorption system. *Applied Energy*. 2017;206:507-18.

[40] Metcalf SJ, Critoph RE, Tamainot-Telto Z. Optimal cycle selection in carbon-ammonia adsorption cycles. *International Journal of Refrigeration*. 2012;35(3):571-80.

[41] Lu Y, Roskilly AP, Tang K, Wang Y, Jiang L, Yuan Y, et al. Investigation and performance study of a dual-source chemisorption power generation cycle using scroll expander. *Applied Energy*. 2017;204:979-93.