

Jiang L, Lu YJ, Roskilly AP, Wang RZ, Wang LW, Tang K.

[Exploration of ammonia resorption cycle for power generation by using novel composite sorbent.](#)

Applied Energy 2018, 215, 457-467.

Copyright:

© 2018. This manuscript version is made available under the [CC-BY-NC-ND 4.0 license](#)

DOI link to article:

<https://doi.org/10.1016/j.apenergy.2018.02.034>

Date deposited:

01/05/2018

Embargo release date:

20 February 2019



This work is licensed under a [Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International licence](#)

Exploration of ammonia resorption cycle for power generation by using novel composite sorbent

L. Jiang^{a,b}, Y.J. Lu^b, A.P. Roskilly^b, R.Z. Wang^a, L.W. Wang^a, K. Tang^b

^a *Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai, 200240, China*

^b *Sir Joseph Swan Centre for Energy Research, Newcastle University, Newcastle NE1 7RU, UK*

Abstract: Expanded natural graphite and carbon coated nickel are selected as the additives in the development of novel composite sorbent. Improved thermo-physical properties of composite strontium chloride result in a faster sorption reaction rate than that without using carbon coated metal. A case study of ammonia-based resorption power generation cycle with two identical reactors is analyzed in terms of sorption characteristics of composite sorbents. Power could be generated in both half cycles, which greatly enhances working versatility and thermal efficiency. It is indicated that additive of carbon coated nickel has a positive influence on performance of resorption power generation cycles. Energy and exergy efficiency of basic resorption cycle range from 0.072 to 0.116 and from 0.402 to 0.737, respectively. Basis resorption cycle for power generation is also compared with improved resorption cycle by using different composite sorbents. Increment between improved and basic resorption cycle by using the sorbent without carbon coated nickel is larger than that using that with carbon coated nickel. Energy density by using novel composite sorbent is improved by up to 20% based on mass and volume of sorption reactor. Through reheating process, performance of basic resorption cycle is further improved by 3-5 times.

Keywords: Sorption; Power generation; Composite sorbent; Energy and exergy efficiency

* This paper is a substantial extension of short version of the conference paper presented at 9th International Conference on Applied Energy (ICAE2017) on August 21-24, Cardiff, UK. Original paper title 'Investigation on a novel composite sorbent for improved sorption characteristic'.

* Corresponding author. Tel. +86-21-34206309
Email: maomaojianglong@sjtu.edu.cn (L. Jiang)

Nomenclature

c_p	Specific heat capacity ($\text{kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$)
Ni@C	Carbon coated nickel
Q	Heat (kJ)
R	Gas constant ($\text{kJ}\cdot\text{kmol}^{-1}\cdot\text{K}^{-1}$)
SrCl_2	Strontium chloride
v	Sorption rate ($\text{kg}\cdot\text{kg}^{-1}\cdot\text{s}^{-1}$)
W	Power (kJ)
x	Sorption capacity ($\text{kg}\cdot\text{kg}^{-1}$)

Abbreviations

<i>COP</i>	Coefficient of performance
<i>E</i>	Exergy (kJ)
<i>ED</i>	Energy density
ENG	Expanded natural graphite
<i>m</i>	Mass (kg)
<i>P</i>	Pressure (Pa)
<i>T</i>	Temperature ($^{\circ}\text{C}$)
<i>t</i>	Time (s)

Greek letters

ΔH	Reaction enthalpy of sorbent ($\text{kJ}\cdot\text{kmol}^{-1}$)
ΔS	Reaction entropy of sorbent ($\text{kJ}\cdot\text{kmol}^{-1}\cdot\text{K}^{-1}$)
η	Efficiency

Subscripts

a	Ambient
con	Condensation
d	Desorption
en	Energy
eq	Equilibrium
ex	Exergy
ENG	Expanded natural graphite

h	Heat
in	Inlet
m	Mass
NH ₃	Ammonia
out	Outlet
R	Reaction
re	Reactor
ref	Refrigeration
reh	Reheating
s	Sorption
salt	Sorbent
sat	Saturation
sen	Sensible
v	Volume
w	Power generation
x	Sorption capacity

1. Introduction

Characterized as sustainable feature and environmental protection, energy conversion technology is gathering the momentum, which could efficiently harness different low grade heat e.g. industrial waste heat, solar energy and geothermal energy [1]. As one of the most promising energy conversion methods, sorption cycle could play various roles of air conditioning and freezing [2], heat pump and energy storage [3], desiccant and desalination [4], CO₂ capture and storage [5], which has aroused a burgeoning number of attentions [6]. In recent decades, integration of sorption cycle with a turbine/expand has opened a new chapter of power generation, which also comes along challenges and opportunities [7]. Thus sorption cycle is able to meet energy demands not only for heat and cold but also for electricity with higher energy grade.

Sorption is generally classified into liquid-gas absorption and solid-gas sorption technology. Liquid-gas absorption power generation cycles have been investigated for several decades. Water-ammonia working pair was first adopted as a pioneer in the 1950s, which verified the possibility

of absorption power generation technology [8]. Afterward, Kalina cycle was proposed for power generation by Dr. Alexander Kalina in 1984 [9]. Different configurations of Kalina cycles were successively introduced to optimize the performance [10]. Also a series of demonstration projects throughout the world has been established based on Kalina cycles. With some modifications of Kalina cycle, Goswami cycle was proposed in 1998 for power and refrigeration cogeneration [11]. In addition to water-ammonia working pair, similar absorption power generation cycle by using LiBr-water working pair was proposed [12, 13]. A variety of advantages e.g. high exergy efficiency could be obtained when compared with conventional Rankine cycle [14]. But this concept was not suitable for small systems due to high volumetric flow rate [15]. Compared to these absorption cycles, solid-gas chemisorption cycles have complementary advantages e.g. large temperature and pressure difference due to its monovariant sorption characteristic, which reveal vast potentials of productive mechanical power generation [16]. Heat and mass transfer enhancement of the sorbent [17] and cycle innovation and optimization [18] are main research fields to accomplish high efficient power generation cycles.

With regard to performance of sorbents, thermos-physical properties e.g. thermal conductivity, permeability and sorption reaction rate are required to be evaluated comprehensively since these parameters are often interdependent. Due to severe swelling and agglomeration phenomenon, granular salts usually display poor heat and mass performance, which will inevitably have a negative influence on sorption and desorption kinetics [19]. Various matrices e.g. expanded natural graphite(ENG) [20], vermiculite [21] and carbon nanoparticle [22] have been attempted as additives in developing composite sorbents, which are considered to be a feasible solution. Among them, ENG is a most investigated material, which is verified as a good additive to improve heat transfer of the sorbent. In most cases, heat transfer and mass transfer are mutually restraint. Mass transfer is slightly weakened by adding ENG. It is worth noting that mass transfer is also a key parameter for thermal performance on some occasions when temperature potential is sufficient for heat transfer of the sorbent. Recently carbon coated metal has proved to be a good matrix for mass transfer enhancement, which could be jointly used with ENG [23]. It was demonstrated that large improvement of sorption cycle in freezing conditions could be achieved for combined heat and cold storage by using carbon coated metal [24]. Thus novel composite sorbent with carbon coated metal is also expected to have a remarkable improvement on sorption power generation cycle.

Additionally, power generation performance could be improved by various advanced cycles such

as sorption cycle [25], resorption cycle [26, 27], advanced resorption cycle [28] and multi-stage resorption cycle [29], These sorption cycles could be applied for both physisorption and chemisorption, which generate the power or achieve cooling and power cogeneration by means of interval heating source, heat and mass transfer recovery, superheating and reheating process [30]. Similar with LiBr-water absorption cycle, physisorption cycles for power generation are relatively difficult for real application since water and methanol-based cycles often work at vacuum pressure, which result in high requirements for the expander [31]. Comparably, several lab-scale ammonia-based sorption systems were established to investigate their cogeneration performance [32, 33]. Except for experimental investigation, theoretical analysis of these power generation cycles all lies in power output and thermal efficiency by using the first and second law of thermodynamics. Nevertheless, power is generally not only related with capacity but also with the time. In some cases, a high power generation rate is also required. It is quite difficult to predict real power output when an expander is integrated into a basic sorption cycle. The main reason is that mass flow rate of working fluid could not be ensured since the expander plays a role as resistance. Sorption or desorption reaction rate will be greatly varied, thus the typical reaction kinetic could not be further utilized.

In this study, sorption and resorption cycle for power generation are presented, and improved resorption cycle is then introduced. ENG and carbon coated nickel (Ni@C) are selected in developing novel composite strontium chloride (SrCl_2), which are conducive to heat and mass transfer performance. Under different working conditions, sorption rate of composite sorbent using Ni@C is accelerated and global conversion rate is increased to some extent when compared with the sorbent not using Ni@C. Thus an improved thermal performance of resorption power generation cycle is assessed in terms of energy output quantity, energy output rate, energy efficiency and energy density. In order to further elaborate the advantages in real application, performance of basic and improved resorption power generation cycle are further compared based on the properties of composite sorbents.

2. Working principle of sorption and resorption cycle for power generation

Basic sorption and resorption cycle for power generation have a same configuration as depicted in Fig.1, which is composed of two vessels and an expander. With respect to sorption type, one vessel acts as a sorption reactor by filling composite sorbent inside while the other vessel plays a role as condenser/evaporator, which is filled with working fluid i.e. ammonia. An expander is placed between

two vessels. The gas pipeline connects two vessels, which is arranged to generate power through the expander. In the first half cycle, sorption reactor is heated to a higher equilibrium condition, which assures enough pressure difference as a driving force of chemical reaction. Power will be generated till ammonia ends up being condensed by condenser. In the second half cycle, condenser will be heated for generating power, which is similar with the process of the first half cycle.

For chemisorption reaction process, working pressure is determined by working temperature, which could be according to equation 1 [34]. Thermodynamic working processes of basic sorption cycle for power generation are plotted, and P - T schematic diagram is indicated in Fig.2 by using reaction of SrCl_2 as an example. In the first half cycle, vessel 1 i.e. sorption reactor is supplied with the heat of Q_{input1} to a high equilibrium pressure at point 1. Vessel 2 serves as condenser, which is cooled by environmental medium at point 3. Ammonia is then desorbed and expanded through the expander to generate the power of W_1 . Isentropic expansion process is presented as 1-2. Vapour expansion process is subject to sorption pressure of P_{sat} as backpressure. The expanded ammonia vapour is then cooled and condensed in the condenser. Thereafter heat and cold source swap their roles, and the second half cycle begins. Condenser serves as an evaporator, which is heated to generate ammonia vapour at point 4. Sorption reactor is cooled by cooling medium. The isobaric superheating process is required to ensure gas expansion as 4-5. These two processes are supplied with heat input of Q_{input2} . Then ammonia expands again to generate power of W_2 from point 5. The ammonia expansion process is assumed to stop when ammonia nearly reaches dew point 6 so that liquid formation in the expander can be avoided. Afterwards the exhausted ammonia is sorbed by sorption reactor at point 7. Since backpressure of the second half cycle of power generation is sorption reaction pressure of SrCl_2 at 30°C i.e. the intersection point of ammonia and SrCl_2 reaction line, it is much lower than ammonia saturated pressure i.e. P_{sat} , which reveals vast potentials of power generation[35].

$$\ln\left(\frac{P_{\text{eq}}}{P}\right) = -\frac{\Delta H_{\text{R}}}{RT_{\text{eq}}} + \frac{\Delta S}{R} \quad (1)$$

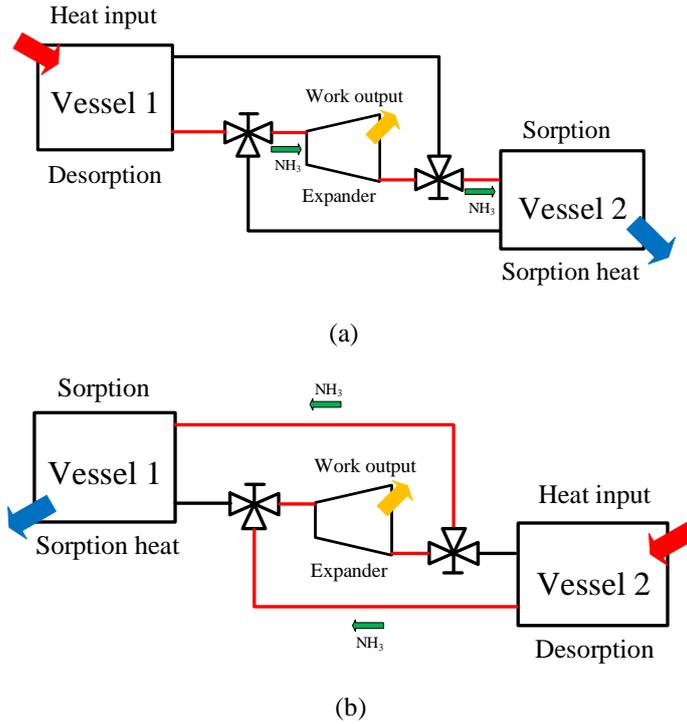


Fig.1. Schematic diagram of basic sorption and resorption power generation cycle (a) the first half cycle; (b) the second half cycle.

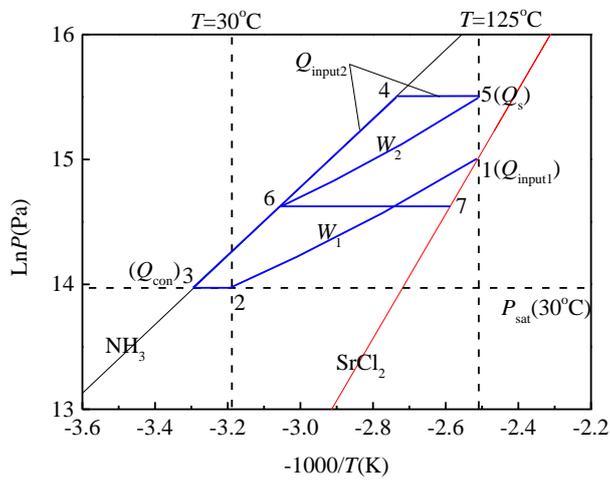
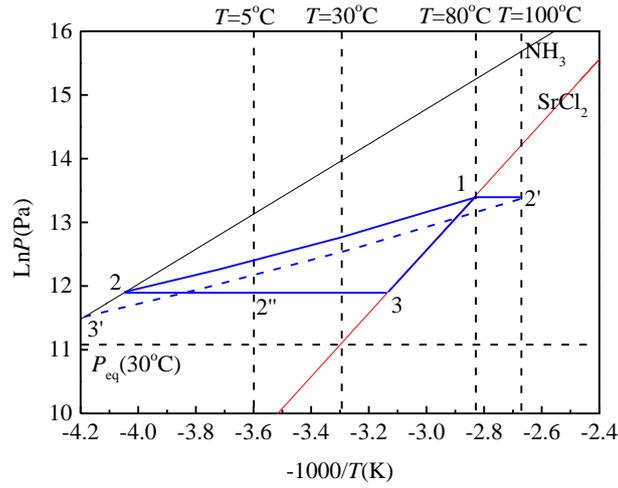


Fig.2. P - T schematic diagram of sorption cycle for power generation by using SrCl_2 .

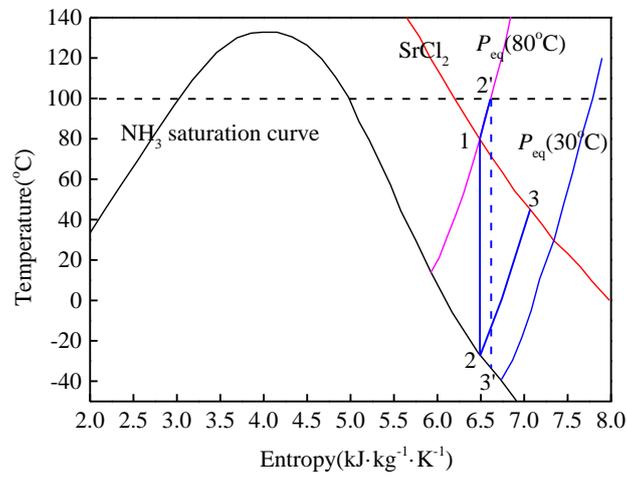
Similar with the configuration of basic sorption power generation cycle as shown in Fig.1, resorption cycle for power generation replaces condenser/evaporator with another sorption reactor i.e. both two vessels are filled with composite sorbents. Two sorption reactors could be adopted with the

same sorbents or two different sorbents to group up a resorption working pair. One major difference between sorption and resorption cycle is that resorption cycle tends to enjoy better performance for power generation under the similar external conditions due to the lower backpressure of another sorbent when compared with ammonia condensation pressure. Also worth noting that no liquid ammonia inside the system is more conducive to system safety. Fig.3 demonstrates of resorption cycle for power generation by using $\text{SrCl}_2\text{-SrCl}_2$. P - T schematic of Fig.3a and T - S schematic of Fig.3b are mutually corresponded. In Fig.3a, SrCl_2 filled in one reactor is heated from point 1 to point 3 whereas the other reactor with same sorbent is cooled from point 3 to point 1. Desorption process happens at point 1 and then ammonia vapour undergoes isentropic expansion process as 1-2. Temperature of expanded ammonia at point 2 is generally lower than refrigeration temperature, which indicates that additional possible cooling power could be recovered by a precooler as 2-2'' shown in Fig.3a. Then the other reactor sorbs the exhausted ammonia vapour from expander at point 3. Similarly, the expansion process also stops when ammonia nearly reaches dew point. After that, two identical sorption reactors change their roles and the second half cycle begins, which is similar with the first half cycle.

One remarkable fact is that $\text{SrCl}_2\text{-SrCl}_2$ working pair has remarkable potentials to generate more power even at a relatively low heat source temperature i.e. low than 120°C if an extra reheating process is applied to basic resorption power generation cycle. The improved resorption power generation cycle is depicted as shown in Fig.4. A heat exchanger is added before the expander for reheating process. As it is shown in Fig.3a and Fig.3b, power output is increased from 1-2 to 2'-3' through the reheating process from 80°C to 100°C . Also pressure and temperature of expanded ammonia become lower than that without reheating process, which probably inhibits the sorption reaction process. Compared with sorption power generation cycle, resorption cycles have the advantage of low desorption temperature and more power output. Thus resorption cycles with two identical sorption reactors i.e. basic and improved cycle will be further elaborated in the rest of paper.

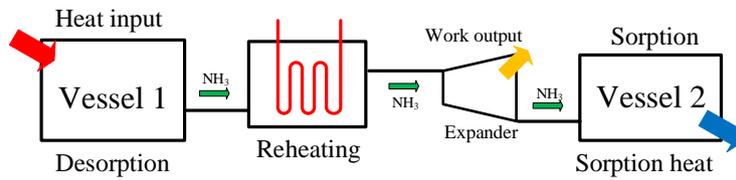


(a)

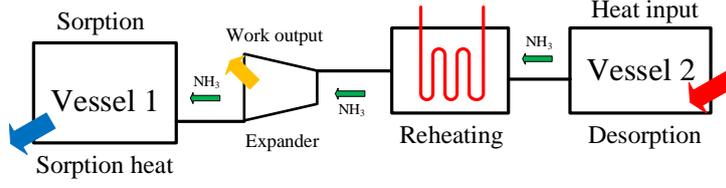


(b)

Fig.3. Schematic diagram of resorption cycle for power generation by using $\text{SrCl}_2\text{-SrCl}_2$ (a) P - T diagram; (b) T - S diagram.



(a)



(b)

Fig.4. Schematic diagram of improved resorption power generation cycle (a) the first half cycle; (b) the second half cycle.

3. Analytical methodology of resorption cycle for power generation

Heat input of resorption cycle for power generation can be expressed as equation 2:

$$Q_{\text{input}} = Q_R + Q_{\text{sen}} + Q_{\text{reh}} \quad (2)$$

where Q_R is reaction heat of sorbent, Q_{sen} is sensible heat, Q_{reh} is the heat in the reheating process.

Sensible heat input could be expressed as equation 3, which is composed of ENG, sorbent and ammonia.

$$Q_{\text{sen}} = [(m \cdot c_p)_{\text{ENG}} + (m \cdot c_p)_{\text{salt}} + (m \cdot c_p)_{\text{NH}_3}] \cdot (T_h - T_a) \quad (3)$$

where the first term in the right side of equation 3 is sensible heat consumed by ENG, the second and third term are sensible heat consumed by sorbent and ammonia, respectively, T_h is heating temperature, T_a is ambient temperature.

Heat input in the reheating process could be expressed as equation 4:

$$Q_{\text{reh}} = m_{\text{NH}_3} \cdot c_{\text{NH}_3} \cdot (T_h - T_d) \quad (4)$$

where T_d is desorption temperature.

Exergy input for heating process could be expressed as equation 5:

$$E_{\text{input}} = (1 - T_a / T_h) \cdot Q_{\text{input}} \quad (5)$$

Power generation could be expressed as equation 6:

$$W = E_w = m_{\text{NH}_3} \cdot (h_{\text{out}} - h_{\text{in}}) \quad (6)$$

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

Additional possible cooling power could be expressed as equation 7:

$$Q_{\text{ref}} = m_{\text{NH}_3} \cdot (h_{\text{out}} - h_{\text{ref}}) \quad (7)$$

where h_{ref} is enthalpy in accord with refrigeration temperature.

Energy efficiency of power generation and refrigeration could be expressed as equation 8 and 9,

respectively:

$$\eta_{\text{en,w}} = (W_1 + W_2) / (Q_{\text{input1}} + Q_{\text{input2}}) \quad (8)$$

$$COP = (Q_{\text{ref1}} + Q_{\text{ref2}}) / (Q_{\text{input1}} + Q_{\text{input2}}) \quad (9)$$

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

Exergy efficiency of power generation could be expressed as equation 10:

$$\eta_{\text{ex,w}} = (E_{\text{w1}} + E_{\text{w2}}) / (E_{\text{input1}} + E_{\text{input2}}) \quad (10)$$

Energy density for power generation based on mass and volume of composite SrCl_2 could be expressed as equation 11 and 12, respectively:

$$ED_{\text{m,salt}} = W / m_{\text{salt}} \quad (11)$$

$$ED_{\text{v,salt}} = W / V_{\text{salt}} \quad (12)$$

Energy density for power generation on basis of mass and volume of sorption reactor could be expressed as equation 13 and 14, respectively:

$$ED_{\text{m,re}} = W / m_{\text{re}} \quad (13)$$

$$ED_{\text{v,re}} = W / V_{\text{re}} \quad (14)$$

4. Material development and characterization

Due to suitable reaction temperature and relatively high sorption capacity, SrCl_2 is selected to develop composite sorbent and its thermo-physical properties are investigated in this section. The next section aims to assess the performance of resorption power generation cycles by using the experimental

results of this section. Thermochemical reaction processes of SrCl_2 with ammonia can be referred to equation 15 and 16, respectively. SrCl_2 8/1 is used to simplify description of thermochemical reaction process of SrCl_2 , which represents SrCl_2 ammoniate reacts with ammonia from 1 mole to 8 moles. Also worth noting that SrCl_2 1/0 could not be utilized in selected temperature range i.e. below 120°C . Table 1 indicates the main parameters of SrCl_2 in terms of equilibrium desorption temperature, molar mass, reaction enthalpy, reaction entropy and maximum cycle sorption capacity [36].



Table 1. The main parameters of SrCl_2 [36].

Sorbent	SrCl_2 8/1
Equilibrium desorption temperature ($^\circ\text{C}$)	96 (30 $^\circ\text{C}$ condensation temperature)
Molar mass ($\text{kg}\cdot\text{kmol}^{-1}$)	158.4
Reaction enthalpy ΔH ($\text{kJ}\cdot\text{kmol}^{-1}$)	41432
Reaction entropy ΔS ($\text{kJ}\cdot\text{kmol}^{-1}\cdot\text{K}^{-1}$)	228.6
Maximum cycle sorption capacity Δx_{max} ($\text{kg}\cdot\text{kg}^{-1}$)	0.75

4.1 Development of composite SrCl_2

For heat and mass transfer enhancement of sorbent, ENG and Ni@C are adopted as the additives in the development of composite SrCl_2 . ENG is beforehand expanded by an optimal expanding process, i.e. heating expandable natural graphite in an oven at a temperature of 600°C for 8 minutes, which could refer to our previous work [37]. Detailed developing processes of composite SrCl_2 by using ENG and Ni@C are illustrated in Fig.5. First, Ni@C is dispersed in ethanol with ultrasonic bath for 30 minutes to prevent the aggregation (a_1 process). Meanwhile, SrCl_2 and dried ENG are weighted according to a set mass ratio (a_2 process). Then ENG, Ni@C and SrCl_2 solution are stirred and mixed together in ultrasonic bath for another 30 minutes (b process). After that, the mixture will be dried in an oven at 200°C for 48 hours (c process). Composite sorbent development is then complete, and it will be

put into a vessel and pressed by compression machine (d process). Finally, consolidated composite sorbent will be transferred into sample mold for testing thermal conductivity (e_1 process) as well as sorption characteristics (e_2 process). The development of composite SrCl_2 with ENG is similar, which is not concerned with a_1 process.

Density of composite SrCl_2 with ENG and Ni@C is selected from $500 \text{ kg}\cdot\text{m}^{-3}$ to $1000 \text{ kg}\cdot\text{m}^{-3}$, which covers the range by using different filling methods for sorption reactors. Mechanical and thermal stability could be ensured during the testing process. Mass ratio between SrCl_2 and ENG is selected as 80% whereas mass ratio between ENG and Ni@C is adopted as 20:1 [38]. Only plate samples are tested for optimal heat transfer direction i.e. testing direction is perpendicular to compression direction.

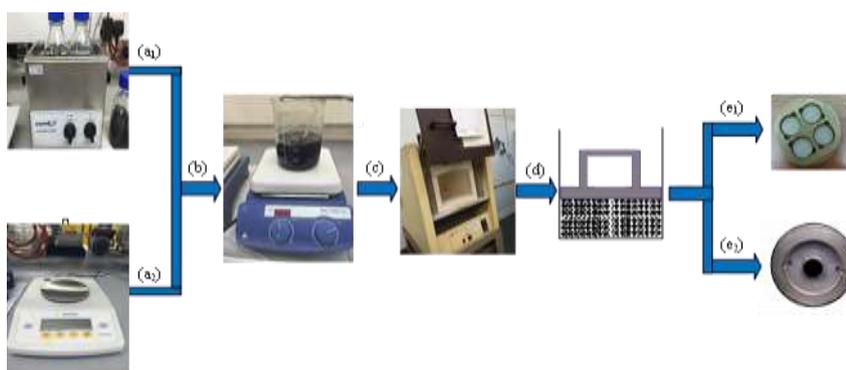


Fig.5. Developing process of composite SrCl_2 with ENG and Ni@C as the additives.

4.2 Thermo-physical and sorption properties of composite strontium chloride

Table 2 demonstrates thermo-physical properties of novel composite sorbent in term of thermal diffusivity, thermal conductivity and permeability. The testing apparatus and method could refer to our previous work of composite sorbent by using ENG and carbon coated aluminum as the additive [23]. The largest relative errors of thermal conductivity and permeability are 5% and 5.15%, respectively.

Since ENG and carbon coated metal have been verified as good additives, enhanced heat and mass

transfer performance is briefly introduced, which is mainly used to elaborate the influence on the improvement of sorption reaction rate. It is indicated that thermal diffusivity and thermal conductivity increase with the increase of density whereas permeability displays a reverse trend. The highest thermal diffusivity and thermal conductivity of novel composite SrCl₂ with ENG and Ni@C could reach 4.67 mm²·s⁻¹ and 2.71 W·m⁻¹·K⁻¹ with density of 1000 kg·m⁻³, which is improved by 10 times when compared with performance of granular salt. Considering different densities ranging from 500 kg·m⁻³ to 1000 kg·m⁻³, thermal diffusivity and thermal conductivity range from 3.63 mm²·s⁻¹ to 4.67 mm²·s⁻¹ and from 1.05 W·m⁻¹·K⁻¹ to 2.71 W·m⁻¹·K⁻¹, respectively. Also worth noting that permeability decreases from 10⁻¹² m² to 10⁻¹⁵ m².

Table 2. Thermo-physical properties of novel composite SrCl₂.

Density (kg·m ⁻³)	500	600	700	800	900	1000
Thermal diffusivity (mm ² ·s ⁻¹)	3.63	4.02	4.25	4.43	4.51	4.67
Thermal conductivity (W·m ⁻¹ ·K ⁻¹)	1.05	1.4	1.7	2.05	2.35	2.71
Permeability (m ²)	4.85×10 ⁻¹²	8.62×10 ⁻¹³	3.88×10 ⁻¹³	9.02×10 ⁻¹⁴	4.85×10 ⁻¹⁴	9.66×10 ⁻¹⁵

With regard to enhanced heat and mass transfer performance of novel composite sorbent, sorption characteristics are also investigated by means of a specifically designed testing unit. The detailed information i.e. testing procedure, principle and structure of this apparatus could refer to our previous research [39].

Fig.6 indicates sorption reaction rate v_x of composite SrCl₂ with ENG and with ENG&Ni@C under the condition of different evaporation temperatures i.e. -30°C, -20°C, 0°C and 20°C and sorption temperature i.e. ambient temperature 30°C, which is evaluated according to equation 17. It tends to conclude that composite sorbent with ENG&Ni@C presents a better sorption performance than that with ENG at low evaporation temperature due to the improved permeability. When evaporation temperature is -30°C and -20°C as shown in Fig.6a and Fig.6b, sorption reaction rate by using composite SrCl₂ with ENG&Ni@C could be accelerated by up to 30% when compared with that using

composite SrCl₂ with ENG. It is demonstrated that mass transfer will become more critical with the decrease of evaporation temperature. When evaporation temperature increases, sorption reaction rate of composite SrCl₂ with ENG and with ENG&Ni@C become close. This could be attributed to the fact that mass transfer of composite sorbent with ENG is improved with the increase of evaporation temperature, and heat transfer performance will gradually take a leading role. For evaporation temperature of 0°C as shown in Fig.6c, sorption rate of composite SrCl₂ with ENG and with ENG&Ni@C begin to partially overlap and gradually become similar as indicated in Fig.6d. It is evident that sorption capacity increases and reaction time decreases with the increase of evaporation temperature. In terms of different evaporation temperatures, sorption reaction rate ranges from 0.1×10^3 kg·kg⁻¹·s⁻¹ to 0.98×10^3 kg·kg⁻¹·s⁻¹ within 5000s reaction time.

$$v_x = \frac{dx}{dt} = \frac{(m_2 - m_1)}{m_{\text{salt}} \cdot (t_2 - t_1)} \quad (17)$$

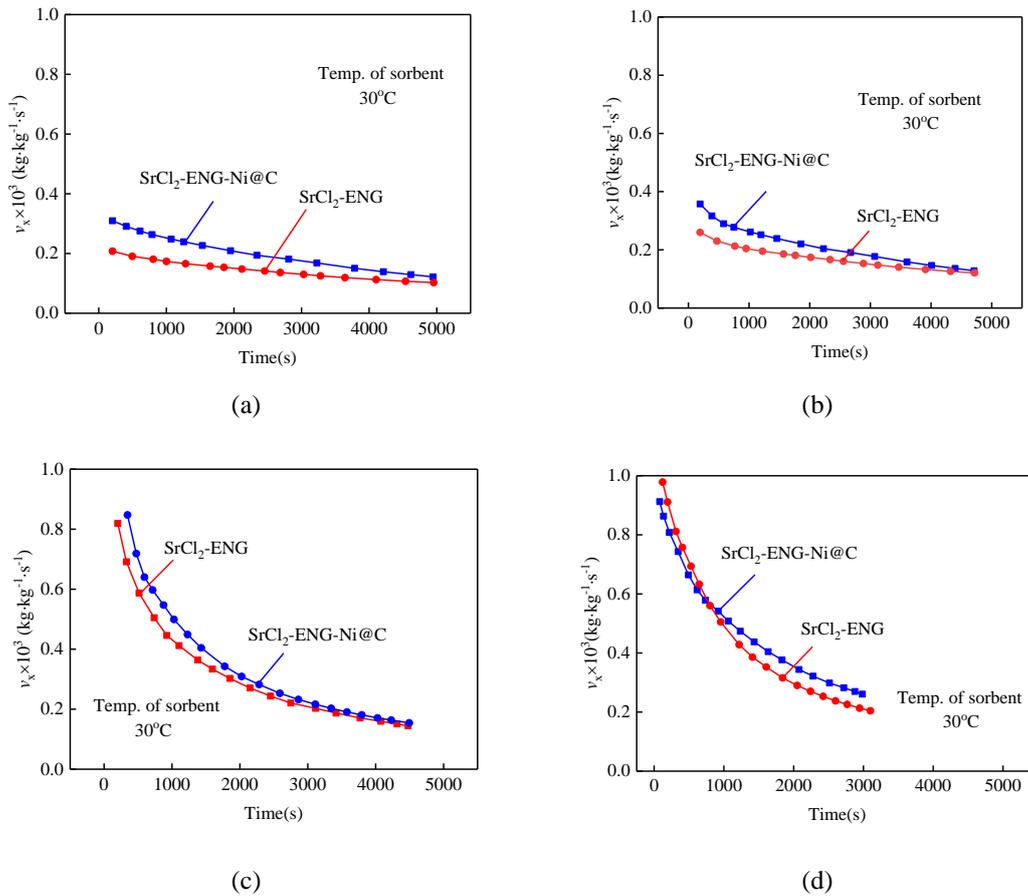


Fig.6. Sorption reaction rate of composite SrCl₂ with ENG and with ENG&Ni@C vs. different

evaporation temperatures (a) -30°C ; (b) -20°C ; (c) 0°C ; (d) 20°C .

5. Results and discussions

Since the expanded ammonia from the outlet of expander first reaches ammonia saturation pressure rather than backpressure of SrCl_2 as analyzed in Fig.3, sorption reaction rate at low evaporation temperature i.e. low constraint pressure will be adopted to evaluate power generation performance of resorption cycle with two identical reactors by filling composite SrCl_2 . One significant fact is that expansion process is assumed to operate under stable condition, i.e. instantaneous mass flow rate of resorption cycle for power generation is the same in all positions. It is admitted that in real application, mass flow rate may fluctuate at different parts of resorption system or even the expander could not be driven at the beginning and the end of power generation process due to the mismatch between resorption system and expander, which will not be considered in this paper. Also the isentropic process is considered as a theoretical process for thermal analysis. This is mainly because this paper aims to compare the performance between resorption power generation cycles by using different composite sorbents. It won't have an influence on performance variation trends by defining a different constant isentropic efficiency [40].

Specific work output and power output of a half resorption cycle are evaluated as shown in Fig.7a and Fig.7b under the condition of 80°C heat source temperature. Compared with resorption power generation cycle by using various sorbents with different equilibrium reaction temperatures, the cycle using the same sorbent has a relatively lower driving temperature. For SrCl_2 - SrCl_2 working pair, the lowest driving temperature is as low as 62°C in terms of 30°C ambient temperature due to the monovariant characteristic of chemisorption reaction characteristic. Thus pressure potential at 80°C heat source temperature is sufficient to drive the expander for power generation. It is worth noting that

basic resorption cycle by using SrCl₂-ENG&Ni@C for two sorption reactors has a better specific work output and power output than that using SrCl₂-ENG. Specific work output increases with reaction time whereas specific power output increases at first then decreases with the increase of reaction time. For power generation times ranging from 0 to 60 min, specific work output ranges from 51.1 kJ·kg⁻¹ to 178.1 kJ·kg⁻¹ by using SrCl₂-ENG&Ni@C which is increased by 27.5% to 6.75% when compared with that using SrCl₂-ENG. The highest specific power output could reach 239.4 kW·kg⁻¹ at 17 minutes by using SrCl₂-ENG whereas the highest value using SrCl₂-ENG&Ni@C is 301.5 kW·kg⁻¹ at 14 minutes. When average power output is required to reach a certain level, power generation time could accordingly be reduced to meet the demand, which increases switching times of resorption cycle, e.g. 30 minutes for power generation means two half working cycles in 60 minutes.

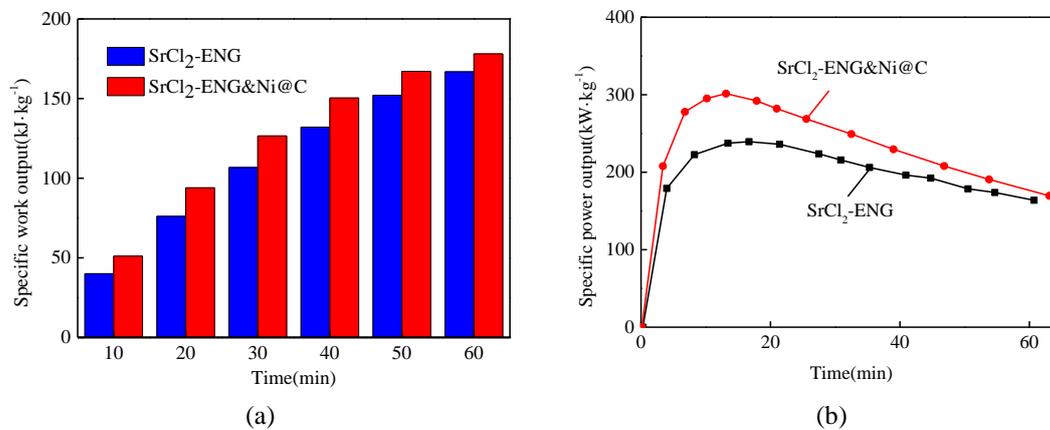


Fig.7. Performance of basic resorption cycle for power generation by using composite SrCl₂ with ENG and ENG&Ni@C vs. power generation time (a) specific work output; (b) specific power output.

Considering specific work output and power output at various reaction times, thirty minutes could be a good selection for investigating the performance at different heat source temperatures since both of output values are relatively high. Specific work output and power output are evaluated under the condition of 80-110°C heat source temperature which are shown in Fig.8. It is indicated that specific

work output and power output increase with the increase of heat source temperature. The results increase slightly with the temperature from 80°C to 100°C. Then increment will become obvious when temperature increases from 100°C to 110°C due to the improved sorption reaction rate of composite sorbent. Specific work and power output of basic resorption cycle by using SrCl₂-ENG&Ni@C are increased by up to 22% when compared with that using SrCl₂-ENG. For different heat source temperatures from 80°C to 110°C, specific work output and power output are in the range from 106.7 kJ·kg⁻¹ to 198.3 kJ·kg⁻¹ and from 215.8 kW·kg⁻¹ to 396.6 kW·kg⁻¹, respectively.

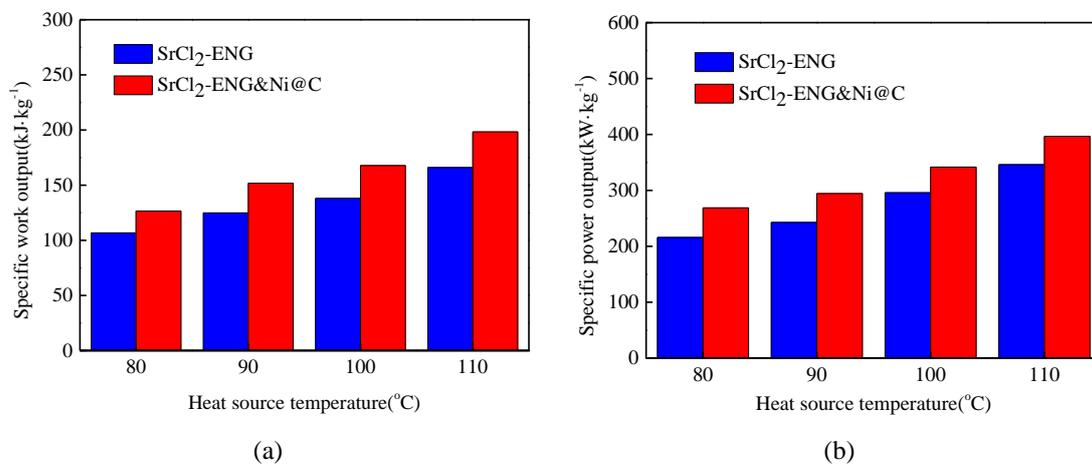


Fig.8. Performance of basic resorption cycle for power generation vs. different heat source temperatures (a) specific work output; (b) specific power output.

Energy efficiency of basic resorption cycle for power generation is evaluated in terms of different heat source temperatures and reaction times, which is indicated in Table 3. Results show that performance of basic resorption cycle by using SrCl₂-ENG is a little different from that using SrCl₂-ENG&Ni@C. Energy efficiency of power generation by using SrCl₂-ENG increases with reaction time from 10 minutes to 60 minutes while performance by using SrCl₂-ENG&Ni@C increases up to 50 minutes then decreases from 50 minutes to 60 minutes. This is mainly because sorption reaction rate by using SrCl₂-ENG&Ni@C is faster than that using SrCl₂-ENG, which leads to the relatively small growth of power generation in comparison with that of heat input after 50 minutes. In regard of different heat source temperatures, energy efficiency increases from 80°C to 100°C and decreases from 100°C to 110°C. Considering similar expansion ratios of basic resorption cycle by using SrCl₂-ENG&Ni@C and SrCl₂-ENG, the main reason for energy efficiency variation is because sorption

global conversion rate is greatly increased at 110°C heat source temperature, which accelerates power generation process. Also worth noting that energy efficiency at temperatures from 80°C to 100°C could be much improved by using SrCl₂-ENG&Ni@C when compared with that from 100°C to 110°C. Low heat source temperature results in low outlet temperature of expander for basic resorption cycle. Thus mass transfer of sorbent takes a leading role in the resorption reaction process. When heat source temperature becomes higher, advantage of mass transfer by using Ni@C will be attenuated, which leads to a relatively small increment of system performance. Under the condition of different heat source temperatures and reaction times, energy efficiency for power generation ranges from 0.072 to 0.116.

Exergy efficiency of power generation by using different composite SrCl₂ is demonstrated in Table 4. Different from energy efficiency of power generation, exergy efficiency by using different composite SrCl₂ decreases with the increase of heat source temperature. By using SrCl₂-ENG, exergy efficiency increases with the increase of reaction time. Comparably, exergy efficiency of power generation by using SrCl₂-ENG&Ni@C increases from 10 minutes to 30 minutes and then decreases with the increment of reaction time from 30 minutes to 60 minutes. For basic resorption cycle, exergy efficiency of power generation ranges from 0.402 to 0.737.

Table 3. Energy efficiency of basic resorption cycle for power generation.

Sorbent type	SrCl ₂ -ENG				SrCl ₂ -ENG&Ni@C			
	80°C	90°C	100°C	110°C	80°C	90°C	100°C	110°C
Time/heat source temp.								
10 minutes	0.072	0.075	0.076	0.083	0.086	0.089	0.097	0.096
20 minutes	0.084	0.089	0.094	0.093	0.099	0.104	0.11	0.106
30 minutes	0.088	0.094	0.10	0.099	0.101	0.105	0.113	0.109
40 minutes	0.090	0.095	0.104	0.101	0.102	0.106	0.116	0.110
50 minutes	0.091	0.096	0.105	0.102	0.103	0.108	0.115	0.111
60 minutes	0.092	0.097	0.106	0.105	0.099	0.105	0.114	0.114

Table 4. Exergy efficiency of basic resorption cycle for power generation.

Sorbent type	SrCl ₂ -ENG				SrCl ₂ -ENG&Ni@C			
	80°C	90°C	100°C	110°C	80°C	90°C	100°C	110°C
Time/heat source temp.								
10 minutes	0.509	0.454	0.408	0.402	0.609	0.543	0.512	0.46
20 minutes	0.598	0.544	0.503	0.446	0.701	0.637	0.588	0.507
30 minutes	0.625	0.56	0.553	0.466	0.737	0.694	0.639	0.525
40 minutes	0.640	0.568	0.555	0.481	0.727	0.655	0.617	0.527

50 minutes	0.648	0.581	0.562	0.483	0.724	0.652	0.614	0.529
60 minutes	0.654	0.586	0.566	0.501	0.692	0.631	0.609	0.547

In order to have an comprehensive comparison between basic resorption cycle and improved resorption cycle by using different composite SrCl_2 , energy and exergy efficiency are further evaluated at different heat source temperatures, which are shown in Fig.9. Thirty minutes are still selected as reaction time due to reasonable energy efficiency and optimal exergy efficiency. One striking fact is that improved resorption cycle for power generation has a better thermal efficiency than that of basic resorption cycle by using the same composite sorbent. This is mainly because increment of power generation is higher than that of extra sensible heat input in reheating process. Also worth noting that increment between improved cycle and basic cycle increases with the increase of heat source temperature since the higher heat source temperature with larger reheating temperature difference results in more power output. Increment between improved and basic resorption cycle by using $\text{SrCl}_2\text{-ENG}$ is larger than that between cycles by using $\text{SrCl}_2\text{-ENG\&Ni@C}$. Thus novel composite sorbent takes priority when considering the system compactness since improved resorption cycle will add a heat exchanger for reheating process. For different heat source temperatures, energy and exergy efficiency of improved resorption cycle for power generation range from 0.115 to 0.142 and from 0.62 to 0.81, respectively.

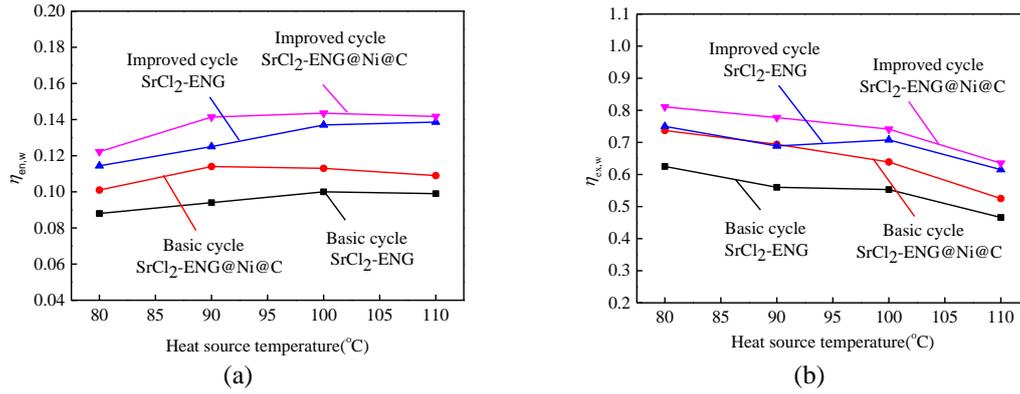


Fig.9. Energy and exergy efficiency of basic and improved resorption cycle for power generation vs. different heat source temperatures (a) energy efficiency; (b) exergy efficiency.

Energy density is regarded as a key parameter which is used to evaluate the performance of resorption power generation cycle. The general evaluation of energy density is defined as the ratio between power output and mass or volume of composite sorbent. Fig.10 indicates energy density of basic resorption cycle for power generation at different heat source temperatures. It is demonstrated that Ni@C has a positive influence on mass energy density and volume energy density of power generation. The largest improvement of energy density by using SrCl₂-ENG&Ni@C could reach 1.13 times higher than that by using SrCl₂-ENG. For different heat source temperatures from 80°C to 110°C, energy densities based on mass and volume of composite SrCl₂ are in the range from 46.5 kJ·kg⁻¹ to 83.1 kJ·kg⁻¹ and from 58.1 MJ·m⁻³ to 103.8 MJ·m⁻³, respectively.

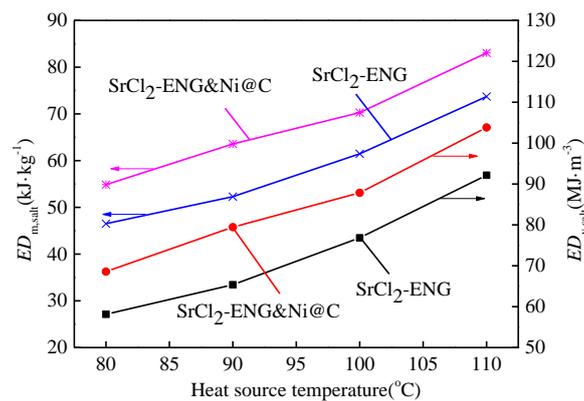


Fig.10. Energy density of basic resorption cycle for power generation based on mass and volume of composite SrCl₂ vs. different heat source temperatures.

Nonetheless, in real application it is not appropriate to analyze energy density based on mass and volume of sorbents since metal part of sorption reactor usually accounts for a majority of mass and volume. Given various types of sorption reactors and filling methods, relation between sorbents and reactors is quite different. Thus mass and volume ratio between reactor and sorbent are defined to evaluate the possible energy densities of basic resorption cycle at 80°C heat source temperature, which are indicated in Fig.11. When mass and volume ratio range from 1 to 10, energy densities based on mass and volume of sorption reactor range from 4.99 kJ·kg⁻¹ to 27.4 kJ·kg⁻¹ and from 6.2 MJ·m⁻³ to 34.3 MJ·m⁻³, respectively. The current researches on sorption reactors mainly lie in finned tube and non-finned tube by using compressing and non-compressing methods, and the concerning mass and volume ratios between reactor and sorbent are in the range from 2 to 9 and from 2 to 7, respectively[23]. It is evident that compressing method has a higher energy density due to a lower mass and volume ratio [41], which is more suitable for real application with a relatively compact structure. Thus mass and volume ratio by using compressing method are selected for evaluating the performance under the condition of 80-110°C heat source temperature, which are demonstrated in Fig.12. It is worth noting that energy densities based on mass and volume of sorption reactor show a similar trend with that by using mass and volume of composite sorbent, which range from 10.3 kJ·kg⁻¹ to 18.5 kJ·kg⁻¹ and from 19.4 MJ·m⁻³ to 34.6 MJ·m⁻³, respectively.

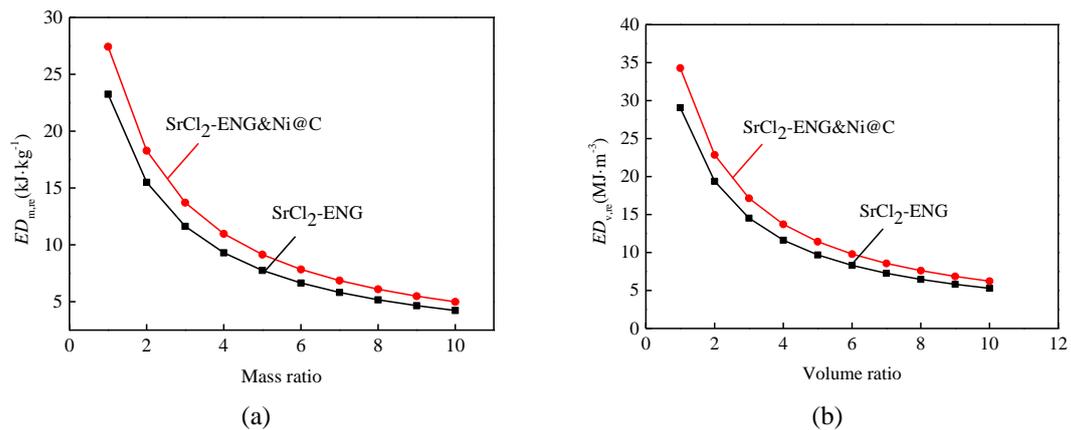


Fig.11. Energy density of basic resorption cycle for power generation vs. different mass and volume ratios between sorbent and reactor (a) mass energy density; (b) volume energy density.

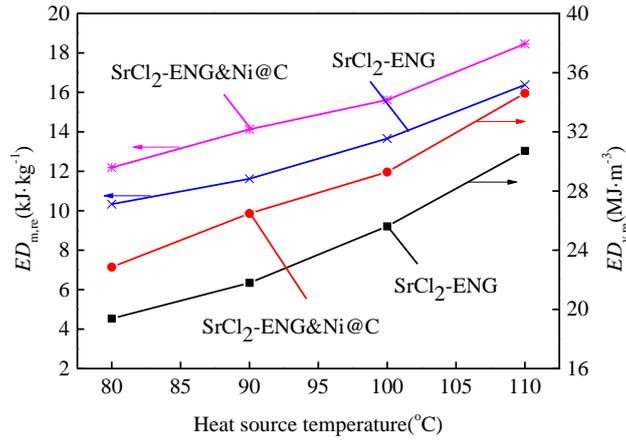


Fig.12. Energy density of basic resorption cycle for power generation based on mass and volume of sorption reactor vs. different heat source temperatures.

Under the condition of 30 minutes reaction time and different heat source temperatures from 80°C to 110°C, energy densities based on mass and volume of sorption reactor are further compared in terms of basic and improved resorption cycle for power generation, which are indicated in Table 5. Considering power generation density, composite sorbent and cycle improvement both take effects on the extra output. By using SrCl₂-ENG&Ni@C, Energy density based on mass and volume of sorption reactor is improved by up to 20%, which could maintain simple structure without any modification to basic resorption cycle. Comparably through reheating process of improved resorption cycle, performance of basic resorption cycle is further improved by 3-5 times. For real application, energy density should be calculated based on mass and volume of sorption system, which will provide more practical perspectives. With regard to resorption cycle for power generation, two identical sorption reactors serve as the major apparatus. Thus system energy densities of resorption cycles by using mass and volume of sorption reactor are still representative, which are slightly smaller than that using mass and volume of sorption system.

Table 5. Comparison of energy density for power generation based on different resorption cycles.

Cycle type	Basic resorption cycle		Improved resorption cycle	
	ED _{m,rc} (kJ·kg ⁻¹)	ED _{v,rc} (MJ·m ⁻³)	ED _{m,rc} (kJ·kg ⁻¹)	ED _{v,rc} (MJ·m ⁻³)
SrCl ₂ -ENG	3.9-20.5	7.3-38.4	23.5-71.7	22-61.4
SrCl ₂ -ENG&Ni@C	4.6-22.3	8.7-41.9	25.6-75.9	24.4-62.8

As discussed above in Fig.3, the possible cooling power could be obtained when the outlet temperature of expander is lower than refrigeration temperature. Nonetheless, the calculated results are quite small, and the highest *COP* of basic resorption cycle is only 0.03 under the condition of 30 minutes reaction time and 80°C heat source temperature. *COP* of basic resorption cycle decreases with the increase of heat source temperature. Comparably, refrigeration performance of improved resorption cycle is even unsatisfactory due to the extra heat input of reheating process. Thus it is of little significance to recover cooling power from resorption power generation cycle especially considering metal part of the precooler in real application, which also reduces the system compactness and safety.

Although sorption technology has various functions of power generation, heat storage and upgrade, combined heating and cooling, power and refrigeration cogeneration, one remarkable fact is that various output is bound to have a limit with a certain capacity of heat input. This paper is to maximize power generation of resorption cycle by using novel composite sorbent and reheating process. Thus refrigeration could not be further utilized. It is necessary to select a proper sorption technology in accord with different demands and applications. Therefore, a guideline will be our future work to have a comprehensive comparison among different sorption technologies.

6. Conclusions

An improved performance of resorption power generation cycle is achieved based on novel composite sorbent, which is developed by using additives of ENG and Ni@C. Better heat and mass transfer of novel composite sorbent are conducive to sorption characteristic. Performance of basic and improved resorption cycle by using different composite SrCl₂ are further compared in terms of different reaction times and heat source temperatures. Conclusions are yielded as follows:

- (1) Thermal diffusivity and thermal conductivity increases with the increase of density whereas permeability displays a reverse trend. For densities from $500 \text{ kg}\cdot\text{m}^{-3}$ to $1000 \text{ kg}\cdot\text{m}^{-3}$, thermal diffusivity, thermal conductivity and permeability range from $3.63 \text{ mm}^2\cdot\text{s}^{-1}$ to $4.67 \text{ mm}^2\cdot\text{s}^{-1}$, from $1.05 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ to $2.71 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ and from 10^{-12} m^2 to 10^{-15} m^2 , respectively. Composite SrCl_2 with $\text{ENG}\&\text{Ni}\text{@C}$ show a better sorption characteristic than that with ENG at low evaporation temperatures. For different evaporation temperatures, sorption reaction rate ranges from $0.1\times 10^3 \text{ kg}\cdot\text{kg}^{-1}\cdot\text{s}^{-1}$ to $0.98\times 10^3 \text{ kg}\cdot\text{kg}^{-1}\cdot\text{s}^{-1}$ within 5000s.
- (2) Resorption cycle by using $\text{SrCl}_2\text{-ENG}\&\text{Ni}\text{@C}$ has a better specific work output and power output than that using $\text{SrCl}_2\text{-ENG}$. Specific work output ranges from $51.1 \text{ kJ}\cdot\text{kg}^{-1}$ to $178.1 \text{ kJ}\cdot\text{kg}^{-1}$ by using $\text{SrCl}_2\text{-ENG}\&\text{Ni}\text{@C}$ which is increased by 27.5% to 6.75% when compared with that using $\text{SrCl}_2\text{-ENG}$. The highest specific power output could reach $239.4 \text{ kW}\cdot\text{kg}^{-1}$ at 17 minutes by using $\text{SrCl}_2\text{-ENG}$ whereas the highest value using $\text{SrCl}_2\text{-ENG}\&\text{Ni}\text{@C}$ is $301.5 \text{ kW}\cdot\text{kg}^{-1}$ at 14 minutes.
- (3) Energy efficiency of basic resorption cycle by using $\text{SrCl}_2\text{-ENG}$ increases with reaction time while performance by using $\text{SrCl}_2\text{-ENG}\&\text{Ni}\text{@C}$ increases first then decreases. Also energy efficiency increases from 80°C to 100°C and decreases from 100°C to 110°C . By using $\text{SrCl}_2\text{-ENG}$, exergy efficiency increases with the increase of reaction time whereas exergy efficiency of resorption cycle by using $\text{SrCl}_2\text{-ENG}\&\text{Ni}\text{@C}$ increases first and then decreases from 30 minutes to 60 minutes. Energy and exergy efficiency for power generation of basic resorption cycle range from 0.072 to 0.116 and from 0.402 to 0.737, respectively.
- (4) $\text{Ni}\text{@C}$ has a positive influence on mass and volume energy density of power generation. Energy densities based on mass and volume of composite sorbent range from $46.5 \text{ kJ}\cdot\text{kg}^{-1}$ to

83.1 kJ·kg⁻¹ and from 58.1 MJ·m⁻³ to 103.8 MJ·m⁻³. Energy densities based on mass and volume of sorption reactors show a similar trend with that by using composite sorbents, which range from 10.3 kJ·kg⁻¹ to 18.5 kJ·kg⁻¹ and from 19.4 MJ·m⁻³ to 34.6 MJ·m⁻³, respectively.

- (5) Novel composite sorbent and cycle improvement both take effects on the extra power output. Energy density by using SrCl₂-ENG&Ni@C is increased by up to 20% based on mass and volume of sorption reactor whereas performance of basic resorption cycle is further improved by 3-5 times through reheating process of improved resorption cycle.

As energy conversion technology driven by low grade heat is gather the momentum, integration with the expander reveals more possibilities of sorption cycles. Resorption power generation cycles could be an alternative method to meet requirement of electricity by recovering various forms of heat source e.g. solar energy, geothermal energy and waste heat since it has a driving temperature lower than 120°C. One suitable application is to recover industrial waste heat, which may be used a sub-cycle after Rankine cycle like current ORC technology. Electricity output could be applied for auxiliary equipment e.g. water pump, cooling fan, heater, etc. Except for its thermal efficiency, resorption cycles for power generation have a function of energy storage. It could be complete for the place where electricity output is excessive.

Acknowledgements: This research was supported by National Natural Science Foundation of China under contract number (51606118), foundation for Innovative Research Groups of National Natural Science Foundation of China (51521004) and Centre for Energy Systems Integration (EP/P001173/1) funded by Engineering and Physical Science Research Council of UK.

References

- [1] Yan J, Chou S-K, Desideri U, Lee D-J. Transition of clean energy systems and technologies towards

- a sustainable future (Part I). *Applied Energy*. 2015;160(Supplement C):619-22.
- [2] 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.
- [3] 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.
- [4] Jagirdar M, Lee PS. Mathematical modeling and performance evaluation of a desiccant coated fin-tube heat exchanger. *Applied Energy*. 2018;212:401-15.
- [5] Zhao R, Deng S, Liu Y, Zhao Q, He J, Zhao L. Carbon pump: Fundamental theory and applications. *Energy*. 2017;119:1131-43.
- [6] Freni A, Sapienza A, Glaznev IS, Aristov YI, Restuccia G. Experimental testing of a lab-scale adsorption chiller using a novel selective water sorbent “silica modified by calcium nitrate”. *International Journal of Refrigeration*. 2012;35(3):518-24.
- [7] 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.
- [8] Maloney J, Robertson R. Thermodynamic study of heat power cycles. Oak Ridge National Laboratory Report. 1953:CF-53-8-43.
- [9] 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.
- [10] 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.

[11] 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.

[12] Novotny V, Vodicka V, Mascuch J, Kolovratnik M. Possibilities of water-lithium bromide absorption power cycles for low temperature, low power and combined power and cooling systems. Energy Procedia. 2017;129:818-25.

[13] Novotny V, Mascuch J, Tsai H-Y, Kolovratnik M. Design of Experimental Rig for Validation of Absorption Power Cycle Concept. Energy Procedia. 2017;105:4990-6.

[14] Garcia-Hernando N, de Vega M, Soria-Verdugo A, Sanchez-Delgado S. Energy and exergy analysis of an absorption power cycle. Applied Thermal Engineering. 2013;55(1):69-77.

[15] Shokati N, Ranjbar F, Yari M. A comparative analysis of rankine and absorption power cycles from exergoeconomic viewpoint. Energy Conversion and Management. 2014;88:657-68.

[16] 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.

[17] Jiang L, Wang LW, Jin ZQ, Wang RZ, Dai YJ. Effective thermal conductivity and permeability of compact compound ammoniated salts in the adsorption/desorption process. International Journal of Thermal Sciences. 2013;71:103-10.

[18] 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(Supplement C):920-48.

[19] Jiang L, Gao J, Wang L, Wang R, Lu Y, Roskilly AP. Investigation on performance of multi-salt composite sorbents for multilevel sorption thermal energy storage. Applied Energy. 2017;190:1029-38.

- [20] Zhao YJ, Wang LW, Wang RZ, Ma KQ, Jiang L. Study on consolidated activated carbon: Choice of optimal adsorbent for refrigeration application. *International Journal of Heat and Mass Transfer*. 2013;67:867-76.
- [21] Veselovskaya JV, Tokarev MM, Grekova AD, Gordeeva LG. Novel ammonia sorbents “porous matrix modified by active salt” for adsorptive heat transformation: 6. The ways of adsorption dynamics enhancement. *Applied Thermal Engineering*. 2012;37:87-94.
- [22] Grekova A, Gordeeva L, Aristov Y. Composite sorbents “Li/Ca halogenides inside Multi-wall Carbon Nano-tubes” for Thermal Energy Storage. *Solar Energy Materials and Solar Cells*. 2016;155:176-83.
- [23] 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.
- [24] Jiang L, Wang RZ, Lu YJ, Roskilly AP, Wang LW, Tang K. Investigation on novel modular sorption thermal cell with improved energy charging and discharging performance. *Energy Conversion and Management*. 2017;148(Supplement C):110-9.
- [25] Bao H, Wang Y, Roskilly AP. Modelling of a chemisorption refrigeration and power cogeneration system. *Applied Energy*. 2014;119:351-62.
- [26] 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.
- [27] 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.

- [28] 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.
- [29] 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.
- [30] Jiang L, Lu H, Wang R, Wang L, Gong L, Lu Y, et al. Investigation on an innovative cascading cycle for power and refrigeration cogeneration. *Energy Conversion and Management*. 2017;145:20-9.
- [31] 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.
- [32] 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.
- [33] Jiang L, Wang LW, Liu CZ, Wang RZ. Experimental study on a resorption system for power and refrigeration cogeneration. *Energy*. 2016;97:182-90.
- [34] 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(Supplement C):67-74.
- [35] Bao H, Ma Z, Roskilly AP. An optimised chemisorption cycle for power generation using low grade heat. *Applied Energy*. 2017;186:251-61.
- [36] 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.
- [37] Jin Z, Tian B, Wang L, Wang R. Comparison on Thermal Conductivity and Permeability of Granular and Consolidated Activated Carbon for Refrigeration. *Chinese Journal of Chemical*

Engineering. 2013;21(6):676-82.

[38] Wu Q, Yu X, Zhang H, Chen Y, Liu L, Xie X, et al. Fabrication and thermal conductivity improvement of novel composite adsorbents adding with nanoparticles. Chinese journal of mechanical engineering. 2016;6:1114-8.

[39] 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(Supplement C):767-79.

[40] Jiang L, Wang L, Wang R, Gao P, Song F. Investigation on cascading cogeneration system of ORC (Organic Rankine Cycle) and CaCl₂/BaCl₂ two-stage adsorption freezer. Energy. 2014;71:377-87.

[41] Jiang L, Wang RZ, Wang LW, Liu JY, Gao P, Zhu FQ, et al. Performance analysis on a novel compact two-stage sorption refrigerator driven by low temperature heat source. Energy. 2017;135(Supplement C):476-85.