A chemisorption power generation cycle with multi-stage expansion driven by low grade heat

Huashan Bao, Zhiwei Ma*, Anthony Paul Roskilly

Sir Joseph Swan Centre for Energy Research, Newcastle University, Newcastle upon Tyne NE1 7RU, UK

Abstract

Ammonia-based chemisorption cycle driven by low grade heat exhibits vast potential for power generation because there exists huge pressure difference between the two salt-adsorbent-filled reactors. However, the intrinsic feature of ammonia as a wet fluid and the difficult match between chemisorption cycle and expansion device impede the development of such a power generation system and also increase the difficulty of practical implementation. To explore maximum benefits of this technology, the present work has proposed and studied a new resorption power generation cycle that applies multiple expansion. The application of multiple expansion integrated with reheating processes aims to overcome the limitation of the ammonia being wet fluid and fully harness the huge pressure difference that chemisorption can offer for power generation, leading to the improvement of energy efficiency. The performance of the proposed multiple expansion resorption power generation cycle using three typical resorption salt pairs, including sodium bromide – manganese chloride, strontium chloride – manganese chloride and sodium bromide – strontium chloride, have been investigated not just based on theoretical thermodynamics but also with the consideration of practical factors to obtain better understanding and more insights for a real system design. The multiple expansion resorption power generation using sodium bromide – manganese chloride and sodium bromide – strontium chloride pairs can achieve 100–600 kJ/kg (ammonia) work output when heat source temperature is from 30 °C to 150 °C; the multiple expansion using strontium chloride – manganese chloride pair has higher average work output per one expansion stage than that using the other two pairs. The cyclic energy efficiency can be achieved as 0.06–0.15 when implementing 2–4 expansions in a more practical scenario where the equilibrium pressure drop is set to 2 bar and the heat source temperature is in the range of 80–150 °C. Such efficiencies are circa 27–62% of Carnot efficiency under the same thermal conditions.

1. Introduction

Sorption technology has been recognised to play a major role in the low carbon future for energy demand of heating, or cooling, or power [1]. Sorption refrigeration and heat pump have received widespread attention and intensive researches and development in recent decades [2]; meanwhile sorption cycle has been recognised as one of the promising energy storage technology due to the inherent intermittence, high energy density and almost zero energy loss for storage [3]. Since Maloney and Robertson [4] among the first studied ammonia-water based absorption power generation cycle, sorption power generation started to attracted a great deal of research interests to explore more potential of this technology. A typical sorption power generation cycle is Kalina cycle, which was proposed around 1980s [5]. It was followed by a thriving growth of the family of Kalian Cycle System (KCS) [6], some of which have been applied to large scale demonstrators across the world [7]. Goswami cycle, the combination of an ammonia-based Rankine cycle and an ammonia-water absorption cycle, was proposed in 1995 to produce cold and power simultaneously [8]. Compared to liquid absorption cycle, ammonia-based solid chemisorption cycles have the commendable advantage of large pressure difference and the unique reaction equilibrium, which indicates a potential of productive mechanical power generation with more resistance to the limitation of ammonia as a wet fluid [9].

The basic configuration of an ammonia-based chemisorption cycle consists of one salt adsorbent reactor and one condenser/evaporator [10]; while an ammonia-based resorption cycle replaces the condenser/evaporator with a secondary adsorbent reactor [11]. This secondary salt in resorption cycle...
Wang et al. [13] conceptually studied the co-generation of cooling was 160 pair in three-bed configuration when the heat source temperature be about 64 W/kg (adsorbent) by using AQSOA-Z02/water working simulation results predicted the maximum specific power could operating with different adsorption/desorption time ratio. The bed configurations of such physisorption cogeneration system based on two-bed physisorption cycles using AQSOA-Z02 (SAPO-

The results from the aforementioned works motivate and inspire authors to optimise chemisorption cycle, especially resorption cycle for maximising power generation and the efficiency of energy utilisation. Comparing to basic solid sorption cycle either chemisorption or physisorption, ammonia-based resorption power generation (RPG) cycle potentially has even higher pressure ratio for the expansion of working fluid, especially when high pressure ammonia vapour is desorbed by LTS as the inlet fluid of the expander and low pressure is created by HTS adsorption as the back pressure of the expander [20]. However, the main challenge to achieve the expected performance of chemisorption power generation is to, first of all, mitigate the drawback of the ammonia being wet fluid that imposes limitation on fully harnessing the huge pressure difference for power generation; secondly but equally importantly, to have suitable expansion devices that match with the fluid flow of sorption cycles [15]. Because the working fluid flow of chemisorption processes is characterised at the following two points, (1) the mass flow rate can violently change along the process, as it typically peaks highly at the very beginning due to the fast reaction and drops heavily afterwards; (2) the pressure ratio between two reactors, i.e. the ratio of the expander inlet pressure to the backpressure, can be as high as a few tens or even hundreds [20]. Such a wet fluid flow with high pressure ratio and unstable mass flow rate poses a challenge for expansion device selection and operation.

An advanced RPG cycle (abbreviated as A-RPG cycle in the following context) with the aid of a reheating process was proposed to make better use of the huge pressure ratio and mitigate the significant limitation of ammonia being wet fluid [20]. The premise of operating such an A-RPG cycle was to identify the optimal desorption temperatures. According to the theoretical thermodynamic analysis, the total work output can be improved by 10–600% in an A-RPG cycle compared with the basic RPG cycle, depending on desorption salt pairs (MnCl2-NaBr, MnCl2-SrCl2, and SrCl2-NaBr pair were studied in [20]) and heat source temperature (70–200 °C); the increment of energy and exergy efficiency can be achieved as 6–24% and 50–85%, respectively. Moreover, MnCl2-SrCl2 pair is prominently superior to the other studied pairs for A-RPG cycle.

Nevertheless, there is still room for improvement on the power generation. Using single stage expansion, the A-RPG cycle is yet not prominently superior to the other studied pairs for A-RPG cycle.

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been considered in the performance analysis in the previous work. Therefore, a further upgraded cycle is proposed and analysed in this work with the goal of maximising the potential for productive power generation through multiple expansion, which is defined as multiple stage RPG (M-RPG) cycle. The performance of the M-RPG cycle has been evaluated not just based on theoretical thermodynamics under non-equilibrium conditions but also with practical considerations taken into account to provide more practical insights for real system design. The number of expansion stages were discussed from the perspective of the system compactness and cost effectiveness. Meanwhile, three typical resorption salt pairs, NaBr-MnCl₂, SrCl₂-MnCl₂, and NaBr-SrCl₂ having been studied for A-RPG cycle in the previous work [20] will be also discussed in the current work for the comparison between the A-RPG cycle and the M-RPG cycle.

2. Thermodynamic principle

Three salts are discussed in the present work and they are manganese chloride (MnCl₂), strontium chloride (SrCl₂) and sodium bromide (NaBr), representing salts at different temperature levels. The coordination reaction of each salt ammoniate with the ammonia can be formulated as Eqs. (1)–(3).

\[
\text{MnCl}_2 + 2\text{NH}_3 \leftrightarrow \text{MnCl}_2 \cdot 6\text{NH}_3 + 4\Delta H, \quad (1)
\]

\[
\text{SrCl}_2 + \text{NH}_3 + 7\text{NH}_3 \leftrightarrow \text{SrCl}_2 \cdot 8\text{NH}_3 + 7\Delta H, \quad (2)
\]

\[
\text{NaBr} + 5.25\text{NH}_3 \leftrightarrow \text{NaBr} \cdot 5.25\text{NH}_3 + 5.25\Delta H, \quad (3)
\]

The schematics of the basic RPG cycle and the A-RPG cycle proposed in [20] are shown in Figs. 1 and 2, respectively, and they are both comprised of two reversible half-cycles. The thin arrows in the schematics denote the flow direction of the working fluid (the ammonia vapour in this work) and the wider arrows represent the energy flows. Compared to the basic RPG cycle, the A-RPG cycle uses an additional heat exchanger (as denoted as “HE” in Fig. 2) to conduct a reheating process of the desorbed ammonia vapour before its expansion.

The M-RPG cycle schematised in Fig. 3 employs more heat exchangers and expanders to fully realise the great potential of chemisorption power generation. The number of heat exchanger and expander inside the dash-dot-line box in Fig. 3, as denoted as “i”, is changeable depending on different scenarios. It should be noted that the multiple expansion has prominent advantage especially when the pressure difference between two reactors is sufficiently high but the vapour expansion is significantly limited by the saturation condition of the ammonia. Since there is great pressure difference between LTS desorption and HTS adsorption (the second half-cycle defined in this work), it is beneficial for the second half-cycle to apply this multiple expansion concept as it can effectively improve power generation; while there is only moderate or small pressure difference between HTS desorption and LTS adsorption (the first half-cycle), then the multiple expansion is not suitable for this half-cycle in the view of avoiding worthless and complex operation. Therefore in the current work, a complete M-RPG cycle consists of a first half-cycle using optimal single expansion (developed in A-RPG cycle in [20]) and a second half-cycle using multiple expansion. Certainly, a reheating process is necessitated before each expansion except for the first expansion in the multiple expansion process.

The multiple expansion process of the M-RPG cycle is shown and compared with the optimal single expansion process in A-RPG cycle in Fig. 4, where the resorption pair of MnCl₂-SrCl₂ is used as an example. These two processes have the same heat source temperature at 140 °C and the heat sink temperature at 25 °C. The curve labelled as “MnCl₂ (6-2NH₃)” is the equilibrium of the coordination reaction between MnCl₂ ammoniates with the ammonia, as Eq. (1) shows the form of MnCl₂ ammoniate changes as an example. These two processes have the same heat source temperature at 140 °C and the heat sink temperature at 25 °C. The “Peq (25 °C) MnCl₂” represents the equilibrium pressure of the MnCl₂ ammoniates reaction in Eq. (1) when the temperature is at 25 °C. In the multiple expansion process, i.e. the second half-cycle of the M-RPG cycle, the desorption of SrCl₂ ammoniate occurs at 140 °C (point 1), and the desorbed ammonia vapour expands at the expander as the first power generation (curve 1–2); this vapour expansion terminates once the ammonia reaches its saturation line (point 2) due to the requirement of dry expansion for healthy and durable expander operation. Since the expander backpressure, i.e. the adsorption pressure of MnCl₂ ammoniate in this case, is extremely low when the heat sink temperature is at 25 °C, there is still considerable room to develop further expansions if the exhaust from this first expansion is reheated to a higher temperature and moved away from saturated state. In Fig. 4, the exhausted vapour experiences the first reheating process (curve 2–3) using the same heat source before it carries out the second expansion (curve 3–4); likewise, more expansions can be conducted if pressure difference is still available and reheating process is properly applied. In this principle, there can be four stages of vapour expansion with three reheatings in this M-RPG process, and the terminal state of the ammonia vapour is at point 8, which is limited by the expander backpressure, i.e. adsorption pressure of MnCl₂ ammoniate at 25 °C.

The A-RPG cycle developed in literature [20] proposed to obtain maximum power generation through an optimal single expansion. Such an optimal expansion requires to use an optimal desorption temperature. In theory of monovariant resorption cycle, using different desorption temperature results in the different corresponding working pressure; the desorption process in one reactor can occur at different temperatures as long as the corresponding working pressures is higher than the adsorption pressure in the other reactor. If the desorbed ammonia, i.e. the expander inlet vapour, is reheated to the given heat source temperature, certainly, the higher the desorption pressure (the expander inlet pressure) is, the more the generated work output is when it is free from the

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**Fig. 1.** Schematic of basic RPG cycle. (a) the first half-cycle: HTS desorption while LTS adsorption; (b) the second half-cycle: LTS desorption while HTS adsorption.
limitation of the ammonia saturation. However, when the ammonia saturation condition has a significant impact on the expansion, there exists an optimal expander inlet condition. Hence, the A-RPG concept is to find out the optimal desorption temperature for the most productive vapour expansion. The curve 1–2–3 and 1–2–3 in Fig. 4 are two examples using the heat source at 140°C/176°C. The desorption temperatures at the points 1 and 1 are lower than 140°C/176°C while the reheating points 2 and 2 are at 140°C. It is noticeable that the process 1–2–3 generates more work output than the process 1–2–3. Comparing all different possible arrangement of desorption temperature when exhaust reheating is at a given heat source temperature, it can be found that the curve of the optimal expansion with the maximum work output has the terminal state point at the most left part of the grey-marked region, like the point 3. The grey-marked region in Fig. 4 is the area where the pressure is higher than the backpressure but lower than the ammonia saturation pressure of the corresponding temperature; in the meantime, the temperature is higher than the ammonia triple point temperature. Once the final point of the optimal expansion is determined, the location of point 2' and 1' can be reversely deduced according to the rule of isentropic expansion and isobaric heating.

Under the same conditions discussed in Fig. 4, the complete M-RPG cycle and A-RPG cycle are illustrated and compared in T-S diagram in Fig. 5. These two cycles have the same first half-cycle when MnCl₂ ammoniate desorption and SrCl₂ ammoniate adsorption, as represented by the curve 1–2–3. MnCl₂ ammoniate desorption occurs at 140°C (point 2) because this is the optimal desorption temperature identified according to the principle of single optimal expansion. In the second half-cycle, the M-RPG uses multiple expansion and reheating: SrCl₂ ammoniate is first heated to the heat source temperature (3°C/4) then 4–5, 6–7, 8–9, 10–11 represent the isentropic expansion while 5–6, 7–8, 9–10 represent the isobaric reheating processes; the A-RPG operates another single optimal expansion in the second half-cycle, as SrCl₂ ammoniate desorbs at the optimal desorption temperature (point 4'), then the desorbed ammonia is reheated to 5', followed by the expansion 5'–6'.

### 3. Calculation methods

The current study focused on the performance evaluation and efficiency analysis of mechanical work generation. In fact, apart from mechanical work, the expansion exhausts also has the potential of generating considerable amount of cooling power, however, it is not considered in this work. Energy efficiency analysis should be based on a complete cycle that consists of two half-cycles. The influence of external devices and peripheral equipment, such as thermal mass of metallic container, heat transfer coefficient of the heat exchanger and expander efficiency, on the cyclic performance is not taken into consideration. Expanded graphite as the porous inert matrix has been proven its satisfactory efficacy of enhancing thermal conductivity and eliminating the swelling and agglomeration of solid composite [22–24]. The mass ratio of the salt and expanded graphite is 3:1 in this work.

The total thermal energy is mainly consumed by sensible heat load of solid composite (Q\text{en}), desorption heat of salt ammoniate
and the reheating of the ammonia vapour \( Q_{\text{reheat}} \), as expressed in Eq. (4).

\[
Q_{\text{input}} = Q_{\text{sen}} + \Delta H_r \cdot \Delta x + Q_{\text{reheat}} \tag{4}
\]

The heat capacity of salt ammoniate is expressed as the sum of the heat capacities of the salt, expanded graphite and that of the ammonia in a condensed phase [25]. The calculation of sensible heat, \( Q_{\text{sen}} \), in Eq. (5a) is for the cases when desorption occurs at the heat source temperature \( T_s \), while Eq. (5b) should be used when an optimal desorption temperature is used in the case of optimal single expansion.

\[
Q_{\text{sen}} = \left[ (m \cdot c_p(T))_{\text{EG}} + (m \cdot c_p(T))_{\text{salt}} + (m \cdot c_p(T))_{\text{NH}_3} \right] \cdot (T_s - T_e) \tag{5a}
\]

\[
Q_{\text{sen,de}} = \left[ (m \cdot c_p(T))_{\text{EG}} + (m \cdot c_p(T))_{\text{salt}} + (m \cdot c_p(T))_{\text{NH}_3} \right] \cdot (T_{\text{de}} - T_s) \tag{5b}
\]

The consumed thermal energy, \( Q_{\text{reheat}} \), in the reheating processes of multiple expansion can be calculated by Eq. (6a), where the \( T_{\text{exh}} \) denotes the exhaust temperature of the ammonia vapour expansion, e.g. point 2, 4, or 6 in Fig. 4 and \( i \) represents the number of reheating processes; while for optimal single expansion, the \( Q_{\text{reheat}} \) is expressed as Eq. (6b).

\[
Q_{\text{reheat}} = \sum_i m_{\text{NH}_3} \cdot (h(T_s) - h(T_{\text{exh}})) \tag{6a}
\]

\[
Q_{\text{reheat}} = m_{\text{NH}_3} \cdot (h(T_s) - h(T_{\text{de}})) \tag{6b}
\]
For each expansion, the mechanical energy output of the assumed isentropic expansion can be calculated by the following equation.

\[
W = m_{\text{NH}_3} \cdot (h_w - h_{\text{aux}})
\]  

(7)

The energy efficiency of mechanical energy output can be calculated by Eq. (8).

\[
\eta_{\text{en},w} = \frac{(W_1 + W_2)}{(Q_{\text{input}1} + Q_{\text{input2}})}
\]  

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

Three typical halide salts, \(\text{MnCl}_2\), \(\text{SrCl}_2\) and \(\text{NaBr}\), group three different resorption salt pairs, which were studied to evaluate the performance of the M-RPG cycle driven by the heat source between 30 \(^\circ\)C and 150 \(^\circ\)C and the heat sink temperature at 25 \(^\circ\)C. The physical and chemical parameters used in the calculation are summarised in Table 1 [26–28].

4. Equilibrium drops and practical assumption for performance evaluation

The chemisorption requires an equilibrium drop in temperature and pressure (\(\Delta T_{\text{eq}}\) and \(\Delta P_{\text{eq}}\)) versus thermodynamic equilibrium of the reaction for heat and mass transfer to take place. The equilibrium drop is defined as the difference between the operating condition of the reactive salt and its corresponding equilibrium state, as expressed in Eq. (9).

\[
\Delta P_{\text{eq}} = |P_c - P_{\text{eq}}| \quad \text{or} \quad \Delta T_{\text{eq}} = |T_c - T_{\text{eq}}|
\]  

(9)

In other words, the solid–gas chemisorption takes place when the chemical potential at equilibrium is lower than the chemical potential of adsorbed ammonia. If it is greater than the equilibrium potential, it would aggregate the equilibrium condition.

Aiming to have fewer expansion stages as possible in a practical scenario, the following conditions are fulfilled.

1. If the first expansion that uses the fresh desorbed ammonia vapour has low expansion ratio (<2), lower temperature is used for desorption and subsequently the desorbed vapour is reheated to the heat source temperature for the first expansion. This method is similar to the optimal single expansion concept. Nevertheless, the distinction between them is that the operating desorption temperature of a M-RPG cycle for the first expansion is not the optimal one for the maximum work output but the highest desorption temperature that can realise the expansion ratio value as 2. Setting this expansion ratio threshold as 2 is in the interest of reducing the number of expansion stages, meanwhile, achieving higher average expansion work output in a more compact and cost-effective system. Besides, the expansion ratio of most expanders available in nowadays market is no smaller than 2.

2. Likewise, the last expansion if its pressure ratio is lower than 2. It is noticeable that the exhausts temperature before the potential last expansion is very low. If this last expansion would not be productive it is worthless to invest more thermal energy to reheat the vapour and install one more expander; otherwise it would increase system complexity and construction cost.

5. Results and discussion

Fig. 6(a)–(d) shows the total mechanical work generated by multiple expansion when LTS desorption and HTS adsorption, and the equilibrium pressure drop (\(\Delta P_{\text{eq}}\)) is set to 0 bar (representing the ideal equilibrium condition), 1 bar and 2 bar, respectively. Because NaBr is characterised by much higher equilibrium pressure than the other two salts studied in this work, the M-RPG process using NaBr as LTS can be triggered by the heat source at lowest 30 \(^\circ\)C, regardless of the pre-set values of \(\Delta P_{\text{eq}}\); whereas, the \(\text{SrCl}_2\)-\(\text{MnCl}_2\) pair requires higher temperature heat source, higher than 40 \(^\circ\)C and 50 \(^\circ\)C for effective generation if \(\Delta P_{\text{eq}}\) is 1 bar and 2 bar, respectively. Compared with the results at the ideal equilibrium, work output of the M-RPG process using \(\text{MnCl}_2\) as HTS is reduced by 400–450 kJ/kg(NH3) if increasing the value of \(\Delta P_{\text{eq}}\) to 1 bar; while that of the case using \(\text{SrCl}_2\) as HTS is reduced by around 150 kJ/kg(NH3). The synthesis pressure of \(\text{MnCl}_2\) at the heat sink temperature (25 \(^\circ\)C in this work) at the ideal equilibrium is extremely low (around 0.04 bar) while that pressure of \(\text{SrCl}_2\) is about 0.5 bar. These pressure are the expansion backpressure; if increasing the \(\Delta P_{\text{eq}}\) by 1 bar for the purpose of overcoming the potential mass transfer difficulty in the adsorbent composite, that would degrade the pressure ratio by about 25 times for \(\text{MnCl}_2\) cases but by only twice for \(\text{SrCl}_2\) cases. That explains the bigger disparity between the curves of \(\Delta P_{\text{eq}} = 0\) bar and \(\Delta P_{\text{eq}} = 1\) bar in Fig. 6(a) and (c) than that in Fig. 6(b). Further increase in \(\Delta P_{\text{eq}}\) from 1 bar to 2 bar causes the reduction of around 100 kJ/kg work generation for all three salt pairs studied.

Fig. 6(d) compares the work output by three different salt pairs in the second half-cycle when \(\Delta P_{\text{eq}}\) is at 2 bar. The work output of the cycle using NaBr-\(\text{SrCl}_2\) and NaBr-\(\text{MnCl}_2\) have similar varying tendency and close values against the heat source temperature, which elevates from around 100 kJ/kg to about 600 kJ/kg when the heat source temperature rises from 30 \(^\circ\)C to 150 \(^\circ\)C. Using \(\text{SrCl}_2\)-\(\text{MnCl}_2\) generates the least mechanical work under all the conditions discussed in this work; however, the trend of its curve in Fig. 6(d) suggests that it seems to have the potential to overtake the other two pairs when the heat source temperature is beyond the temperature range studied here.

Fig. 7 reveals the average work output of all expansions in the second half-cycle with different heat source temperature when \(\Delta P_{\text{eq}}\) is at 1 bar and 2 bar. The numbers marked beside each curve indicate the total numbers of expansion stages throughout the

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Table 1

| Salt          | \(\Delta H_{\text{r}}\)  \(\text{J/mol}\) | \(\Delta S_{\text{r}}\)  \(\text{J/(mol K)}\) | Max. uptakes \(\text{g(NH}_3\)/g(salt)}\) | \(c_P\)  \(\text{J/(kg K)}\) |
|---------------|---------------------------------|--------------------------------|---------------------------------|-------------------|
| \(\text{NH}_3\) | NIST (National Institute of Standard and Technology) standard reference database | | 0.540 | 4.144 \(\times (16.2 + 0.00052 \times T(K))\) |
| \(\text{MnCl}_2\) (2–6 \(\text{NH}_3\)) | 47,416 | 228.07 | 0.751 | 4.144 \(\times (18.2 + 0.00244 \times T(K))\) |
| \(\text{SrCl}_2\) (1–8 \(\text{NH}_3\)) | 41,431 | 228.8 | 0.867 | 4.144 \(\times (11.74 + 0.00233 \times T(K))\) |
| \(\text{NaBr}\) (0–5.25\(\text{NH}_3\)) | 30,491 | 208.8 | 0.867 | 4.144 \(\times (11.74 + 0.00233 \times T(K))\) |
Fig. 6. Work output in the second half-cycle of the M-RPG cycle as LTS desorption and HTS adsorption, (a) NaBr-MnCl₂, $\Delta P_{eq} = 0–2$ bar; (b) NaBr-SrCl₂, $\Delta P_{eq} = 0–2$ bar; (c) SrCl₂-MnCl₂, $\Delta P_{eq} = 0–2$ bar; (d) All three salt pairs, $\Delta P_{eq} = 2$ bar.

Fig. 7. Average work output per expansion stage in the second half-cycle of the M-RPG cycle, (a) $\Delta P_{eq} = 1$ bar; (b) $\Delta P_{eq} = 2$ bar.
second half-cycle. The average work output joltingly increases with the heat source temperature and each curve can be segmented into different small segments according to the number of expansion stages. The work output of each small segment smoothly climbs up with the rising heat source temperature. It is noticeable that the beginning of each segment starts from a value that is lower than the last one or two points of the previous segment. In other words, at these turning points between two segments, conducting one more expansion can improve the total work output by 35–55 kJ/kg, depending on different pairs; however, this leads to less compact system and less production per unit of devices. The curves of the M-RPG using NaBr-MnCl₂ and NaBr-SrCl₂ have similar variation pattern because they use the same LTS, and the average work output are relatively gently elevating when the heat source temperature is rising; whereas, the increasing trend of the curve that represents SrCl₂-MnCl₂ M-RPG is much steeper. Such distinguishing variation patterns are mainly caused by different reaction equilibrium between different LTSs and ammonia, as clearly reflected in the T-S diagram of Fig. 8. The process 1–2–3–4 represents the first and second expansion of the M-RPG using NaBr as LTS; while the process 1′–2′–3′–4′ is for the case using SrCl₂ as LTS. The state of the ammonia vapour desorbed from SrCl₂ ammoniate is more distant from the ammonia saturation than that of NaBr ammoniate, therefore the ammonia vapour desorbed from SrCl₂ ammoniate has higher superheated degree which is more favourable for power generation.

Fewer expansions but larger average expansion work output can be expected when using SrCl₂–MnCl₂ than the other two salt pairs. For example, when the heat source is in the temperature range of 120–140 °C, although the total work output using NaBr-MnCl₂ and NaBr-SrCl₂ is about 15–22% higher than that using SrCl₂-MnCl₂ as shown in Fig. 6(d), the latter one only operates two expansions while the former two require four expansions. In this instance, using SrCl₂–MnCl₂ pair might be the preferable choice for a small scale system if system compactness and cost effectiveness is particularly one of the key concerns. Therefore Fig. 7 could be useful reference to decide whether it is worthwhile having one more expansion to pursue more work output. Because HTS has relatively lower desorption pressure than LTS does at the same temperature, the threshold of minimum driving temperature is higher for the first half-cycle than that of the second half-cycle. To have a fair comparison, the same temperature range of heat source is used and analysed for both half-cycles.

The energy efficiency of such a complete M-RPG cycle is analysed and plotted in Fig. 9. Since NaBr and SrCl₂ have closer equilibrium property, the heat source temperature that is applicable for both half-cycles using this pair can be as low as 80 °C; the M-RPG cycle using SrCl₂–MnCl₂ pair requires the driving temperature at least 100 °C when ∆P eq is 1 bar, and it requires at least 110 °C when ∆P eq is 2 bar; the NaBr-MnCl₂ M-RPG cycle has the narrowest applicable temperature range and requires the driving temperature at least 130 °C. The NaBr-SrCl₂ M-RPG cycle with ∆P eq = 1 bar has the highest energy efficiency of 0.09–0.16 in the temperature range of 80–150 °C, which is about 54–61% of the theoretical Carnot efficiency. Apparently, higher ∆P eq leads to lower energy efficiency because that signifies smaller pressure difference for expansion; with increasing ∆P eq by one bar, the energy efficiency is degraded by 10–30%, depending on different pairs and different heat sources.

Taking the operation with ∆P eq = 2 bar as an example, the practical considerations mentioned in Section 4 have been taken into account to predict the cycle performance in a more practical scenario. Fig. 10 shows the contrast between cycle energy efficiencies with and without those considerations. Table 2 gives the numbers of expansion stages in these two cases. The modified M-RPG cycles according to the foregoing practical considerations make almost no difference on energy efficiency compared with basic design when the heat source temperature is in the range of 110–150 °C for all three salt pairs; there is only distinct drops on the efficiency curve of NaBr-SrCl₂ pair at lower heat source temperatures (80–100 °C) and on the curve of SrCl₂-MnCl₂ pair using 150 °C heat source. When SrCl₂ is used as LTS, the first expansion ratio is always larger than 2 under the condition studied in this work; the only one exceptional drop on SrCl₂-MnCl₂ curve at 150 °C heat source is attributed to the omitting of the last

![Fig. 8. The first and second expansion during multiple expansion process using NaBr or SrCl₂ as LTS when the heat source temperature is at 120 °C.](image-url)
expansion, the expansion ratio of which is lower than 2. Since the equilibrium of the NaBr ammoniate is very close to the ammonia saturation, when it is employed as LTS, the first expansion ratio can be lower than 2 once the heat source temperature is higher than 40 °C. That implies the studied practical cycles using either NaBr-SrCl$_2$ or NaBr-MnCl$_2$ all have the modified first expansion, and that is the reason why the practical design has fewer expansions, as shown in Table 2. The efficiency drops of practical

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**Table 2**
The numbers of expansion stage in the second half-cycle with and without practical considerations when Δ$P_{eq} = 2$ bar.

| Heat source temperature | 80 °C | 90 °C | 100 °C | 110 °C | 120 °C | 130 °C | 140 °C | 150 °C |
|-------------------------|------|------|--------|--------|--------|--------|--------|--------|
| NaBr-MnCl$_2$ (O)       | –    | –    | –      | –      | –      | 4      | 4      | 4      |
| NaBr-MnCl$_2$ (P)       | –    | –    | –      | –      | –      | 3      | 3      | 3      |
| NaBr-SrCl$_2$ (O)       | 3    | 3    | 3      | 4      | 4      | 4      | 4      | 4      |
| NaBr-SrCl$_2$ (P)       | 2    | 2    | 2      | 3      | 3      | 3      | 3      | 3      |
| SrCl$_2$-MnCl$_2$ (O)   | –    | –    | –      | 2      | 2      | 2      | 2      | 2      |
| SrCl$_2$-MnCl$_2$ (P)   | –    | –    | –      | 2      | 2      | 2      | 2      | 2      |

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Fig. 9. Energy efficiencies of M-RPG cycles with $\Delta P_{eq} = 1$ bar and $\Delta P_{eq} = 2$ bar.

Fig. 10. Energy efficiencies of the M-RPG cycles with and without practical considerations when $\Delta P_{eq} = 2$ bar.
design using NaBr-SrCl₂ pair with 80–100 °C heat source is again because of the delete of the last expansion.

6. Conclusion

Resorption power generation cycle has been further developed in this work to realize the full potential of pressure difference between the desorption of low temperature and the adsorption of high temperature salt for power generation. Reheating expansion exhaust to carry out multiple expansion is the pivot of the developed cycle, which can overcome the restriction of the ammonia being wet fluid and sufficiently implement the feature of huge pressure difference existing in chemisorption. The power generation performance of multiple expansion using three typical salt pairs has been evaluated when driven by low grade heat in the temperature range of 30–150 °C. Energy efficiency of the M-RPG cycles that has optimal single expansion in the first half-cycle and multiple expansion in the second half-cycle has been studied in the basic design and also in the modified practical design. The primary findings are summarized.

(1) The multiple expansion using NaBr-MnCl₂ and NaBr-SrCl₂ pair can achieve 100–600 kJ work output per kg of working fluid ammonia when the heat source temperature is from 30 °C to 150 °C and the equilibrium pressure drop is 2 bar; while the minimum driving temperature is 50 °C when using SrCl₂-MnCl₂ pair, and its work output increases with the heat source temperature as it reaches 550 kJ/kg with 150 °C heat source.

(2) With the same heat source, the multiple expansion using SrCl₂-MnCl₂ pair requires fewer expansions to fully realize the potential of power generation, meanwhile achieving higher average work output per stage of expansion than the other two pairs studied. One should balance the choice between more total work output by conducting more expansions and more compact system with higher average output per unit of devices.

(3) With reasonable assumption, the studied practical design can reduce the number of inefficient expansion and improve the average expansion work output, ultimately achieving more compact and more cost effective system. The M-RPG cycle energy efficiency of the practical design using three salt pairs studied in this work can be achieved as 0.06–0.15 with 2–4 expansions when the heat source temperature in the range of 80–150 °C and the equilibrium pressure drop is set to 2 bar, which is 27–62% of Carnot efficiency. The M-RPG cycle using NaBr-SrCl₂ pair has the highest energy efficiency among three salt pairs studied.

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