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# 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*

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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

* Corresponding author.
*E-mail address:* zhiwei.ma@newcastle.ac.uk (Z. Ma).

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**Nomenclature**

| | |
|---|---|
| $c_p$ | heat capacity (J/(kg K)) |
| $h$ | enthalpy (J/kg) |
| $\Delta H_r$ | chemisorption enthalpy (J/mol ($NH_3$)) |
| $m$ | mass (kg) |
| $M$ | molar mass (kg/mol) |
| $P$ | pressure (Pa) |
| $Q$ | heat (J) |
| $\Delta S_r$ | chemisorption entropy (J/(mol K)) |
| $T$ | temperature (K) |
| $\Delta T$ | temperature difference (K) |
| $W$ | work (J) |
| $\Delta x$ | global conversion of chemisorption (−) |

*Greeks*

| | |
|---|---|
| $\eta$ | efficiency (−) |

*Subscripts*

| | |
|---|---|
| a | ambient |
| c | constrains |
| de | desorption |
| EG | expanded graphite |
| en | energy |
| eq | equilibrium |
| exh | exhaust |
| h | high |
| in | in |
| input | input |
| l | low |
| m | medium |
| $NH_3$ | ammonia |
| out | out |
| reheat | reheat |
| s | source |
| salt | salt |
| sen | sensible |
| w | work |

differs from the main salt with different equilibrium temperature at the same working pressure, so as one is called high temperature salt (HTS) and the other one is low temperature salt (LTS) [12]. Wang et al. [13] conceptually studied the co-generation of cooling and power using a resorption cycle, and concluded that the promising results of 0.69 and 0.29 exergy efficiencies could be obtained for power generation and refrigeration respectively. Long et al. [14] then experimentally assessed Wang et al.'s concept and demonstrated the technical feasibility, as the testing results showed the maximum cooling power of 2.98 kW and the maximum shaft power of 253 W with 82.3 W average value. Bao et al. [15] conducted experiments on a cogeneration system based on the basic chemisorption cycle using $CaCl_2$ as adsorbent, 3 kW refrigeration and maximum 460 W electricity were obtained. After that, a numerical model has been built to simulate this co-generation cycle using different salt adsorbent pairs at various working conditions, and the results revealed $BaCl_2$ as the best adsorbent which led to 0.39 power generation exergy efficiency and 0.23 refrigeration exergy efficiencies at the desorption temperature of 85 °C [16]. Lu et al. [17] studied the improvement in energy efficiency of Wang et al.'s co-generation cycle by applying heat and mass recovery, and the results indicated that the thermal efficiency of electrical power generation can be improved from 8% to 12% with heat recovery. Al-mousawi et al. [18] parametrically investigated the cogeneration performance of cooling and power based on two-bed physisorption cycles using AQSOA-Z02 (SAPO-34)/water, MIL101Cr/water and Silica-gel/water as working pairs, respectively. Al-mousawi et al. [19] also investigated seven different bed configurations of such physisorption cogeneration system operating with different adsorption/desorption time ratio. The simulation results predicted the maximum specific power could be about 64 W/kg (adsorbent) by using AQSOA-Z02/water working pair in three-bed configuration when the heat source temperature was 160 °C and the adsorption/desorption time ratio was 1/2.

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 resorption salt pairs ($MnCl_2$-NaBr, $MnCl_2$-$SrCl_2$, and $SrCl_2$-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, $MnCl_2$-$SrCl_2$ 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 able to achieve the maximum utilisation of huge pressure difference that the ammonia-based resorption can generously provide. For example, the value of the utilisation ratio in the A-RPG cycle using $MnCl_2$-NaBr pair ranges from 1% to 30% when heat source temperature is lower than 200 °C; the highest utilisation ratio achieved by the A-RPG cycle using $MnCl_2$-$SrCl_2$ pair is around 50% when heat source is at 200 °C. Moreover, the equilibrium pressure drop as the main driving force of chemisorption [21] has not