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An optimised chemisorption cycle for power generation using low grade heat

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HIGHLIGHTS

- A novel advanced resorption power generation cycle with reheating process.
- The optimal desorption temperature needs to be identified for maximum work output.
- Continuous waste heat recovery and work output with single-effect cycle.
- Reheating process improved the total work output by 10–600%.
- Considerable cooling output without compromising maximum work output.

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ABSTRACT

The integration of chemisorption cycle with turbine/expander opens up enormous opportunities of recovering low grade heat to meet different energy demands including heating, cooling and power generation. In the present study, a novel advanced resorption power generation (RPG) cycle with reheating process has been proposed for the first time to significantly improve the thermal efficiency and exergy efficiency of the basic RPG cycle. Such a reheating concept is built on the premise of chemisorption monovariant characteristic and identification of the optimal desorption temperature aiming at producing the maximum work output under the given working conditions. The identified optimal desorption temperature might be lower than the available heat source temperature, and the desorbed ammonia vapour is subsequently reheated to the heat source temperature before it undergoes vapour expansion for power generation. This study explored the potential of the proposed advanced RPG cycle and investigated the system performance using three representative resorption sorbent pairs, including manganese chloride – sodium bromide, manganese chloride – strontium chloride, and strontium chloride – sodium bromide, all with ammonia as the refrigerant. The application of reheating concept can improve the total work output of RPG cycle by 10–600%, depending on different sorbent pairs and different heat source temperatures studied in this work, e.g., when the heat source temperature is at 200 °C, the thermal efficiency is increased by 1.4–4.5 times and the exergy efficiency is boosted by 2.0–8.3 times. Another valuable merit of the proposed RPG cycle is that there is a great potential of considerable amount of additional cooling output without compromising the maximum work output, leading to further improvement of system efficiency. Compared to other bottoming cycles for power generations, the proposed advanced RPG cycle exhibits the highest thermal efficiency when the heat source temperature is between 120 °C and 200 °C.

1. Introduction

There have been massive researches and developing efforts on sorption technology, including absorption and adsorption cycles for air conditioning and refrigeration [1], heat pump and heat transformation [2,3], dehumidification and desalination [4], energy storage [5], etc. Although the current sorption technology encounters challenges not just from technical aspect but also in relation to economical issue as it is trudging towards the fiercely competitive and crucial commercial market, above all different specific reasons, the prevailing argument in favour of sorption systems is the potential of using environmentally friendly refrigerants and harnessing low grade heat, leading to energy efficiency improvement and CO_2 emission reduction [1,2]. Ever since Maloney and Robertson [6] as the first pioneer studied ammonia-water based absorption

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Nomenclature

c_p	heat capacity (J/(kg K))
COP	coefficient of performance (–)
E	exergy (J)
h	enthalpy (J/kg)
ΔH_r	chemisorption enthalpy (J/mol (NH_3))
m	mass (kg)
M	molar mass (g/mol)
P	pressure (Pa)
Q	heat (J)
ΔS_r	chemisorption entropy (J/(mol K))
T	temperature (K)
ΔT	temperature difference (K)
W	work (J)
Δx	global conversion of chemisorption (–)

Greeks

η	efficiency (–)

Subscripts

a	ambient
des	desorption
EG	expanded graphite
en	energy
eq	equilibrium
ex	exergy
input	input
NH_3	ammonia
opt	optimal
ref	refrigeration
reheat	reheat
s	source
salt	salt
sen	sensible
w	work

power generation cycle, and later on the improvement by the Kalina cycle [7] justified the further efforts on this promising technology, more and more researches have been inspired to develop power generation or cogeneration of power and cooling through ammonia-based heat powered cycles, such as the growing family of Kalina cycle systems [8], Goswami cycles [9], absorption power/-cooling combined cycles [10,11], and salt-ammonia chemisorption power generation cycles [12–14].

A few demonstration power plants as well as a couple of commercial ones have been built and implemented based on Kalina cycles across the world, driven by geothermal energy, or solar thermal energy or industrial waste heat [15,16]. With fast-progressing technique in the relevant fields, in the near future it can be expected that Kalina power generation system will enter the real market and exhibit its excellent competitiveness. Compared to absorption based Kalina cycles, the salt-ammonia chemisorption cycle is a discontinuous and less stable process with some shortcomings like heat and mass transfer issue and performance degradation concern due to the involved chemicals. Nevertheless, chemisorption cycle features simpler configuration and diverse sorbents to be suitable for a wider range of operational conditions. On the other hand, Kalina cycles require superheating process to tackle the drawback of the ammonia being a wet fluid; additionally, sufficiently low condensing temperature is necessary to assure the power generation driven by low grade heat, for example, the geothermal power plant in Húsavík, one of successful Kalina cycle power plants in the world so far, is using around 5 °C cooling water melted from the snow-covered mountain [15]. From this point of view, chemisorption power generation cycle has the commendable advantage of more resistance to the limitation of ammonia being wet due to the chemical reaction equilibrium, leading to the potential of more productive generation driven by low grade heat [14,17].

Ammonia-based chemisorption power generation cycle has an expander mounted in between two vessels, i.e., one sorbent reactor and the other one condenser/evaporator. The pipeline arrangement allows reversible flow direction between these two vessels all passing through the expander to achieve power generation in both half-cycles. It benefits from the thermodynamic equilibrium of chemical reaction so that the desorbed ammonia is already at superheated vapour state, suggesting the wet fluid limitation can be significantly alleviated. As an alternative type of chemisorption, resorption system has two sorbent reactors as each reactor contains one kind of reactant salt [18,19]. In a resorption power generation (RPG) cycle, the inlet pressure of the expander is desorption pressure in the sorbent reactor at the upstream of the expander, while the backpressure is adsorption pressure in the other sorbent reactor. Thus there in fact potentially exists a larger pressure ratio to drive the expander rotation compared to conventional one-sorbent chemisorption, in other word, the RPG cycle can create even more favourable atmosphere for ammonia expansion [12,13]. Nevertheless, this great potential cannot be fully harnessed due to again the wet fluid feature and the dryness requirement for the healthy operation of the expander. As reported in the previous work [17], the utilisation efficiency (the ratio value of the actual expansion ratio over the available pressure ratio) is no more than 30%, and the worse thing is that this utilisation efficiency declines with the increase of heat source temperature.

In this work, thermodynamic analysis and optimisation of RPG cycle has been conducted in order to gain better knowledge and explore maximum benefits, as a result an advanced RPG cycle with optimal arrangement of thermal energy supply was proposed for the first time to address the foregoing issue, aiming to mitigate the limitation of ammonia being wet so that to optimally harness the great power generation potential of RPG cycles. The performance improvement compared to the basic RPG cycle was investigated in detail through three representative resorption sorbent pairs, $MnCl_2$–NaBr, $MnCl_2$–$SrCl_2$, and $SrCl_2$–NaBr. The efficacy of power and cooling cogeneration of the proposed advanced RPG cycle was also evaluated. Moreover, the comparison with other bottoming cycles, e.g., organic Rankine cycle, stirling cycle and thermal-electric cycle, was conducted to discuss the competitiveness of this advanced RPG cycle.

2. Working principles

2.1. Thermodynamic principle of RPG cycle

A single-effect ammonia-based chemisorption refrigeration cycle (termed as conventional cycle in the context) consists of one solid sorbent reactor, one condenser/evaporator. A resorption cycle substitutes one secondary reactor containing a secondary solid sorbent for the condenser/evaporator in the conventional cycle. Generally, a resorption heat pump cycle uses two different salts to group up an sorbent pair, e.g., $MnCl_2$–NaBr pair, and they are differentiated by their equilibrium temperatures at the same working pressure so as one is called high temperature sorbent

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