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Analysis of an optimal resorption cogeneration using mass and heat recovery processes ☆

Yiji Lu [a,*], Yaodong Wang [a], Huashan Bao [a], Ye Yuan [a], Liwei Wang [b], Anthony Paul Roskilly [a]

[a] *Sir Joseph Swan Centre for Energy Research, Newcastle University, Newcastle NE1 7RU, UK*
[b] *Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai 200240, China*

HIGHLIGHTS

- Resorption cogeneration for electricity and refrigeration generation.
- Mass and heat recovery to further improve the performance.
- The first and second law analysis.

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ABSTRACT

This paper presents an optimised resorption cogeneration using mass and heat recovery to improve the performance of a novel resorption cogeneration fist proposed by Wang et al. This system combines ammonia-resorption technology and expansion machine into one loop, which is able to generate refrigeration and electricity from low-grade heat sources such as solar energy and industrial waste heat. Two sets of resorption cycle are designed to overcome the intermittent performance of the chemisorption and produce continuous/simultaneous refrigeration and electricity. In this paper, twelve resorption working pairs of salt complex candidates are analysed by the first law analysis using Engineering Equation Solver (EES). The optimal resorption working pairs from the twelve candidates under the driven temperature from 100 °C to 300 °C are identified. By applying heat/mass recovery, the coefficient of performance (COP) improvement is increased by 38% when the high temperature salt (HTS) is $NiCl_2$ and by 35% when the HTS is $MnCl_2$. On the other hand, the energy efficiency of electricity has also been improved from 8% to 12% with the help of heat/mass recovery. The second law analysis has also been applied to investigate the exergy utilisation and identify the key components/processes. The highest second law efficiency is achieved as high as 41% by the resorption working pair $BaCl_2$–$MnCl_2$ under the heat source temperature at 110 °C.

1. Introduction

To reduce the energy consumption of conventional energies, using low-grade heat such as solar energy, industrial waste heat, and geothermal energy attracts ever increasing attentions. The most widely applied energy conversion system is the Rankine cycle, which can generate extra work from low-grade heat source. The efficiency of the Rankine cycle highly depends on the heat source temperature and heat sink temperature. However, the isothermal endothermic and exothermic processes cannot perfectly match the variable temperature of the heat source and heat sink. The Kalina cycle is then proposed by Kalina using ammonia–water as working fluid in 1983 [1], which allows adjustable supply temperature by controlling the concentration of the ammonia–water [2–5]. Compared with the conventional Rankine cycle, the Kalina cycle can give up to 32% more power and produce 10–20% higher exergy efficiency when the heat source temperature is lower than 537 °C [6]. To further improve the exergy efficiency, Goswami developed the Kalina cycle into a combined power and refrigeration system by adding a heat exchanger at the outlet of the expansion machine to retrieve refrigeration [7–9]. However, this cogeneration system suffers from its low refrigeration production,

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* Corresponding author. Tel.: +44 (0)191 246 4849.
E-mail address: y.j.lu@ncl.ac.uk (Y. Lu).

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Nomenclature

COP	coefficient of performance
Cp	specific heat at constant pressure (kJ/kg K)
E	exergy (kJ/kg)
HTS	high temperature salt
h	specific enthalpy (kJ/kg)
LTS	low temperature salt
m	mass flow rate (kg/s)
P	pressure (kPa)
Q	heat (kW)
T	temperature (K)
u	specific internal energy (kJ/kg)
W	power output from expander (kW)

Greek letters

ρ	density (kg/m^3)
η	efficiency
Δx	adsorption/desorption quantity (kg/kg)

Subscripts

am	ammonia
ele	electricity
hr	heat recovery
mr	mass recovery
ref	refrigeration
tot	total

which can only achieve the refrigeration coefficient of performance (COP) at 0.0125 [9].

Resorption is an advanced adsorption technology first proposed and adopted by thermochemical system since 1993 [10]. Resorption system mainly contains two adsorbent beds filled with two different salts. Under the same working pressure, the salt which reacts at lower temperature is called as low temperature salt (LTS), and the other is named as high temperature salt (HTS). Resorption technology uses the desorption heat of the salt to yield refrigeration while the conventional adsorption uses the latent heat of ammonia. Because the desorption heat of salt is almost twice of the latent heat of ammonia, the theoretical cooling capacity of resorption system is larger than that of conventional adsorption system [11,12]. The varied selection of chloride salts which can reversibly react with ammonia allows the resorption cogeneration powered by various temperature sources [13]. Furthermore, no condenser and evaporator are required in resorption system, which enlarges the application of the system under vibration conditions such as heavy duty vehicle and fish boat [14].

Wang et al. first proposed a resorption cogeneration producing power and refrigeration [15]. This originally proposed system shows attractive performance compared with the Goswami cycle under the super heater temperature from 150 °C to 400 °C at 10 °C refrigeration temperature. In this work, an optimal resorption cogeneration system is proposed to further improve the performance by using heat and mass recovery processes. Heat and mass recovery processes have been theoretically analysed and experimentally investigated by many researchers from the 1980s in several chemisorption systems [16–20], which showed considerable improvement with the application of those two methods. In order to have an overall understanding of the resorption cogeneration, the first law analysis is applied to choose the optimal resorption working pair from the twelve candidates under the temperature ranging from 100 °C to 300 °C. To investigate the effect of the heat recovery process, mass recovery process and combined heat/mass recovery processes, four optimal resorption working pairs are further analysed by the first and second law analysis.

2. An optimal resorption cogeneration system

2.1. Principle of the resorption cogeneration

The resorption cogeneration includes two high temperature salts (HTS), two low temperature salts (LTS), an expander, a separated circulator for heat recovery and some accessories. This system is able to provide continuous electricity and refrigeration by switching it between steps 1 and 2, which is shown in Fig. 1.

In step 1, V_1, V_3, V_5, V_{m1}, V_{m2} are closed; V_2, V_4, V_6 are opened. The HTS_1 is heated by the heat source and ammonia vapour flows to the expander. The high pressure ammonia drives the expander to produce electricity while the LTS_1 adsorbs ammonia and rejects the adsorption heat to the environment such as a cooling tower. On the other side of this system, the HTS_2 adsorbs the ammonia from LTS_2 where the refrigeration can be obtained. Step 2 is working as a mirror stage of step 1, where the HTS_2 is heated by the heat source and the LTS_1 generates refrigeration. The V_1, V_3, V_5 are opened and V_2, V_4, V_6, V_{m1}, V_{m2} are closed in step 2, which is illustrated in Fig. 1(b).

Three HTS ($NiCl_2$, $FeCl_3$, $MnCl_2$) and four LTS ($BaCl_2$, $PbCl_3$, $CaCl_2$, $SrCl_2$) are chosen to be analysed in the resorption cogeneration. Their reaction equations are list as follows,

$$NiCl_2 \cdot 2NH_3 + 4NH_3 \Longleftrightarrow NiCl_2 \cdot 6NH_3 + 4\Delta H_{NiCl_2} \tag{1}$$

$$FeCl_3 \cdot 2NH_3 + 4NH_3 \Longleftrightarrow FeCl_3 \cdot 6NH_3 + 4\Delta H_{FeCl_3} \tag{2}$$

$$MnCl_2 \cdot 2NH_3 + 4NH_3 \Longleftrightarrow MnCl_2 \cdot 6NH_3 + 4\Delta H_{MnCl_2} \tag{3}$$

$$SrCl_2 \cdot NH_3 + 7NH_3 \Longleftrightarrow SrCl_2 \cdot 8NH_3 + 7\Delta H_{SrCl_2} \tag{4}$$

$$CaCl_2 \cdot 4NH_3 + 4NH_3 \Longleftrightarrow CaCl_2 \cdot 8NH_3 + 4\Delta H_{CaCl_2} \tag{5}$$

$$BaCl_2 + 8NH_3 \Longleftrightarrow BaCl_2 \cdot 8NH_3 + 8\Delta H_{BaCl_2} \tag{6}$$

$$PbCl_2 \cdot 3.25NH_3 + 4.75NH_3 \Longleftrightarrow PbCl_2 \cdot 8NH_3 + 4.75\Delta H_{PbCl_2} \tag{7}$$

The equilibrium reaction lines and thermodynamic features of the resorption cogeneration are shown in Fig. 2. Lines A and B is the heating process of the ammonia inside the HTS, where Points B and A are on the equilibrium reaction line of the HTS. The isentropic expansion process is represented by line B and C. The refrigeration generation is achieved from Lines D to A and the refrigeration temperature of the system is T_D. In this paper, the environmental temperature is set at 20 °C.

2.2. Heat recovery process

To regenerate the sensible heat from HTS after the heating process, a separate circulator is added between the HTS_1 and the HTS_2. The heat recovery process applies between the step 1 and the step 2 during the switch time. Fig. 3(a) illustrates the principle of the heat recovery process, when the system switches from step 2 to step 1. Lines 3–6 is the heat removed from one of the HTS to preheat the other HTS from Point 1 to Point 5. In ideal heat recovery process, the temperature of Point 5 is the same as the temperature of Point 6 ($T_5 = T_6 = T_{hr}$). The P–T diagrams of the heat recovery process between two HTS are shown in Fig. 3.

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