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Study of a novel dual-source chemisorption power generation system using scroll expander

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Abstract

A dual-source chemisorption power generation system using scroll expander is proposed and studied to recover dual heat sources under various working conditions. The chemisorption power generation system mainly composes of two adsorption beds and two expansion machines for the purpose of recovering low grade heat energy such as solar energy and industrial waste heat into electricity. The performance evaluation of the system with Six Metal Chlorides-Ammonia working pairs and scroll expander as the expansion device has been conducted to identify the optimal operational conditions of the system. Results indicate $MnCl_2$-$SrCl_2$ is the optimal working pair while the first heat source temperature is from 90 ^oC to 220 ^oC. $NiCl_2$-$SrCl_2$ is suitable to be used when the first heat source temperature is higher than 220 ^oC. Considering about the specific energy and operational condition of the scroll expander, the optimal working pair of the system is achieved by $MnCl_2$-$SrCl_2$ while the first heat source temperature from 180 to 200 ^oC and the second heat source temperature from 80 to 90 ^oC. The average specific energy of the system under the suggested conditions can be as high as 102 kJ/kg salts for Mode 1 and 85 kJ/kg salts for Mode 2 with the overall average thermal efficiency at 10%.

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Keywords: Chemisorption, dual-source, Power, Scroll expander

1. Introduction

Chemisorption technology attracts intensively attentions being uses as refrigerator or heat pump because of the high demand of effective, alternative and environmental friendly technologies to recover low grade heat into useful energy since 1970s [1-4]. Several researchers pointed out the chemisorption technology can be potentially integrated with expansion machine to form as power generation system [5-8]. However, the previously proposed and studied chemisorption power generation system can only be adapted with one heat source, which limits the system to be used under the circumstance where various heat source conditions are available and can be recovered such as the coolant and exhaust from Internal combustion engine, and various heat source media from industry. Moreover, previous

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reported studies hardly focused on the investigation of the expander to be optimised integrated with chemisorption technology, which leads the unsatisfactory performance of the power generation part [5-11]. In this paper, a dual-source chemisorption power generation system was proposed and investigated, which can be driven by dual heat sources under various working conditions. The system performance using six working pairs and a geometric studied scroll device were analysed and compared to identify the optimal operational conditions of the system under various working conditions.

2. Design of the system

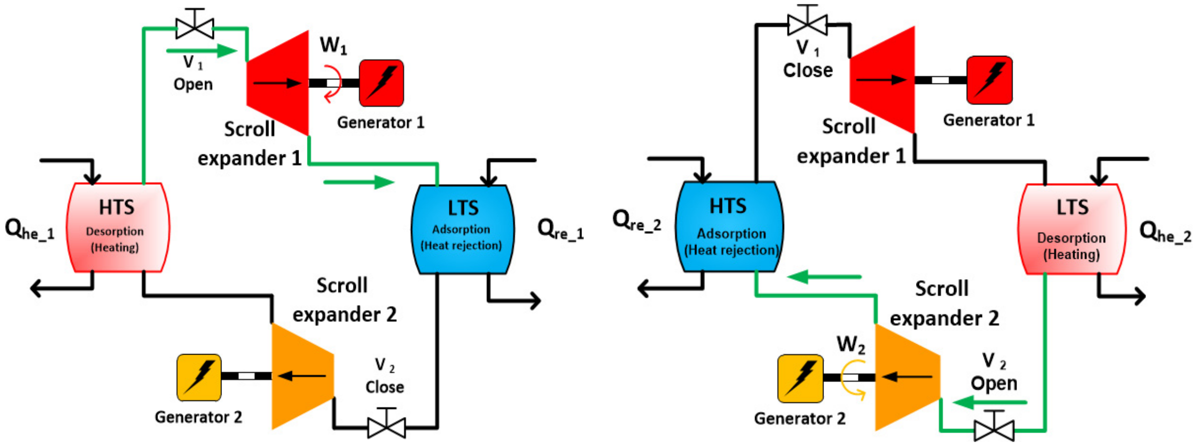


Fig. 1. Schematic diagram of a dual-source chemisorption power generation system
(a) Mode 1, recover the first heat source; (b) Mode 2, recover the second heat source

The dual-source chemisorption power generation system includes a High Temperature Salt (HTS), a Low Temperature Salt (LTS), two scroll expanders and other accessories. The system can be driven by two different heat sources by switching the system between Mode 1 and Mode 2 for continuous electricity generation as indicated in Fig. 1. The Mode 1 is designed to recover the heat source under higher temperature of two heat sources and the Mode 2 is for the recovery of the other heat source. In Mode 1, the HTS consumes the first heat source Q_{he_1} to start the desorption process of the HTS and the ammonia flows from HTS to LTS as indicated in Fig.1 (a). The scroll expander 1 is driven by the evaporated ammonia while the expanded ammonia is adsorbed by the LTS where the adsorption heat Q_{re_1} is rejected to the environment. In Mode 2, the LTS is heated up by the second heat source Q_{he_2} and the evaporated ammonia drives the scroll expander 2 for the power production. The chemical reaction equation of the salt and ammonia can be displayed as equation (1).

$$Me_aCl_b(NH_3)_m \underset{adsorption}{\overset{desorption}{\rightleftharpoons}} Me_aCl_b(NH_3)_n + (m-n)NH_3 \qquad (1)$$

Table 1
Thermodynamic properties of the reaction salts and ammonia [12]

Molecular formula	ΔH (J/mol)	ΔS [J/(mol·K)]	C_p [J/(mol ·K)]	M (g/mol)	Reaction weight with per mol ammonia (g)
NH_3	22839	191.39	80.27(liquid)	17.03	
$BaCl_2$ (8-0)	37665	227.25	75.1	208.23	26.03
$CaCl_2$ (8-4)	41013	230.3	72.52	110.98	27.74
$SrCl_2$ (8-1)	41431	228.8	75.53	158.53	22.65
$MnCl_2$ (6-2)	47416	228.07	72.86	125.84	31.46
$NiCl_2$ (6-2)	59217	227.75	71.6	129.6	32.40

Working conditions of the system are shown in Fig. 2 and can be described as the following processes:

Mode 1, recover the first heat source

1-2: Sensible heat consumption in HTS

2-3: Power generation from Expander 1

3-4: Heat rejection in LTS

Mode 2, recovery the second heat source

4-5: Sensible heat consumption in LTS

5-6: Power generation from Expander 2

6-1: Heat rejection in HTS

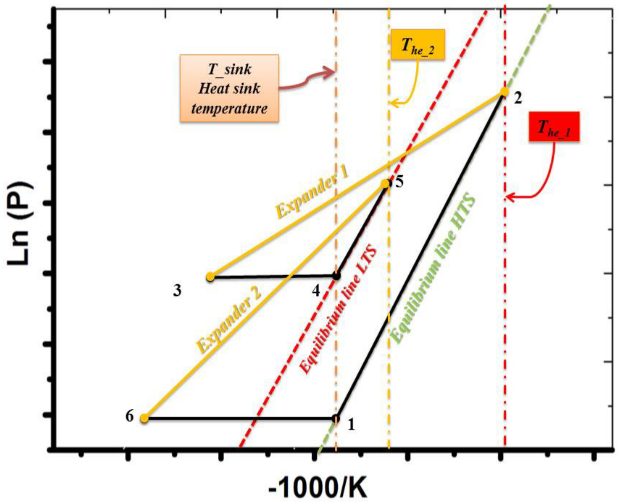


Fig. 2. Clausius-Clapeyron diagram of the dual-source chemisorption power generation system

3. Evaluation methods

The heat provided from two heat sources can be respectively calculated by equation (2) and (3) [7]. The heat consumed from the heat sources includes the reaction heat and sensible heat as shown in the equations, where Δh is the specific reaction enthalpy of the salt, Δx is the chemical conversion ratio, m_{am} is the overall ammonia in the system and C_p is the specific heat capacity. The properties used in the equations can be found in Table 1.

$$Q_{he\_1} = \underbrace{\Delta h_{HTS} \cdot m_{am} \cdot \Delta x}_{reaction\ \ heat\ \ of\ \ HTS} + \underbrace{C_{pHTS} \cdot (T_{he\_1} - T_0) \cdot m_{HTS} + C_{pam} \cdot (T_{he\_1} - T_0) \cdot m_{am}}_{sensible\ \ heat\ \ of\ \ HTS} \tag{2}$$

$$Q_{he\_2} = \underbrace{\Delta h_{LTS} \cdot m_{am} \cdot \Delta x}_{reaction\ \ heat\ \ of\ \ LTS} + \underbrace{C_{pLTS} \cdot (T_{he\_2} - T_0) \cdot m_{LTS} + C_{pam} \cdot (T_{he\_2} - T_0) \cdot m_{am}}_{sensible\ \ heat\ \ of\ \ LTS} \tag{3}$$

The electricity produced from the scroll expanders can be written as following equations [13]. The designed specific enthalpy and pressure in the scroll expander is $h_{d\_exp\_s}$ and $P_{d\_exp\_s}$, respectively. $\eta_{generator}$ is the electrical efficiency of the generator, which is set at 80%.

$$W_{exp\_1} = \left[(h_{he\_1} - h_{d\_exp\_s\_1}) + (P_{d\_exp\_s\_1} - P_3) \cdot v_{d\_exp\_1} \right] \cdot m_{am} \cdot \Delta x \cdot \eta_{generator\_1} \tag{4}$$

$$W_{exp\_2} = \left[(h_{he\_2} - h_{d\_exp\_s\_2}) + (P_{d\_exp\_s\_2} - P_6) \cdot v_{d\_exp\_2} \right] \cdot m_{am} \cdot \Delta x \cdot \eta_{generator\_2} \tag{5}$$

A geometric model has been built in order to calculate of the designed working conditions. The parameters such as suction volume, exhaust volume and swept volume of the scroll device obtained from the geometric model are listed in Table 2.

The thermal efficiency of two modes is calculated by equation (6).

$$\eta_{Mode} = \frac{W_{exp}}{Q_{he}} \tag{6}$$

The specific energy of the chemisorption power system is defined as

$$SP_{Mode} = \frac{W_{exp}}{(m_{HTS} + m_{LTS})} \tag{7}$$

The rotation speed of the scroll expander is calculated from the following equations

Table 2

Parameters of the selected scroll device SANDEN TRSA-09) [14, 15]

Name	Value
Scroll height	33.3 mm
Scroll turns	2.5
Radius of the basic circle	3.2 mm
Pitch of the scroll blade	20.1 mm
Start angle of the involute	40.29 ^{o}
Swept volume	85.7 cm^3
Suction volume	35.04 cm^3
Exhaust volume	105.12 cm^3

$$\dot{m}_{am} = \frac{N}{60} \cdot \frac{V_{SV}}{v_{su}} \quad (8)$$

$$\dot{w}_{exp} = \eta_{Mode} \cdot \dot{Q}_{he} = \frac{W_{exp}}{m_{am} \cdot \Delta x} \cdot \dot{m}_{am} \quad (9)$$

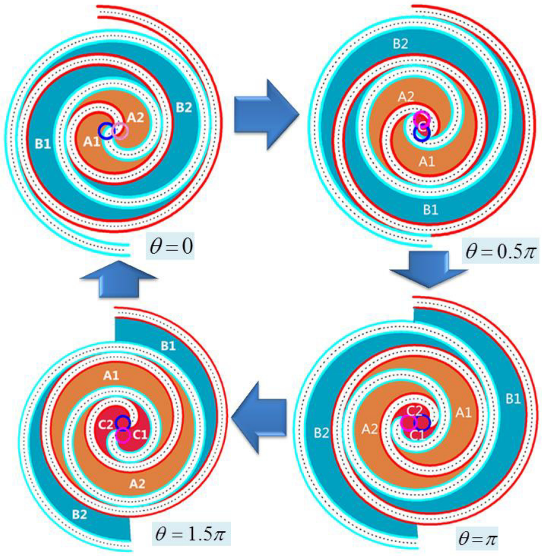
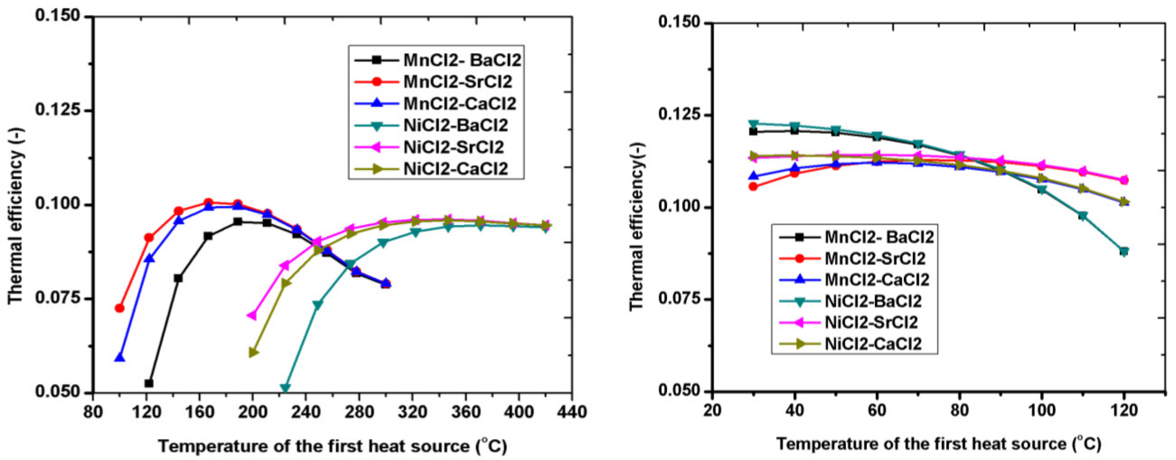


Fig. 3. Expansion process of the scroll device [14]

4. Results and discussion

4.1 Evaluation of thermal efficiency

The comparison of the thermal efficiency of the system using six sorption working pairs and a selected scroll expander in Mode 1 and Mode 2 are shown in Fig.4 (a) and Fig. 4 (b), respectively. In Mode 1, the highest thermal efficiency achieved from the system is about 10% when the heat source temperature is from 160 °C to 180 °C and the $MnCl_2$-$SrCl_2$ is used as the working pair. Moreover, in Mode 1 the optimal thermal efficiency exists in the system when $MnCl_2$ is used to recover the high temperature heat source. The $NiCl_2$ is suitable to be used when the first heat source temperature is higher than 320 °C while the overall thermal efficiency of Mode 1 is about 8%. When the system runs in Mode 2, the thermal efficiency of the system using the six chemisorption working pairs is close to each other as shown in Fig. 4 (b). When the second heat source temperature is lower than 80 °C, the highest thermal efficiency of Mode 2 obtained from the system is around 12% using $BaCl_2$ to recover the heat. The thermal efficiency of Mode 2 using $SrCl_2$ as LTS achieves the highest results among the selected working pairs when the second heat source temperature is ranging from 80 °C to 120 °C.

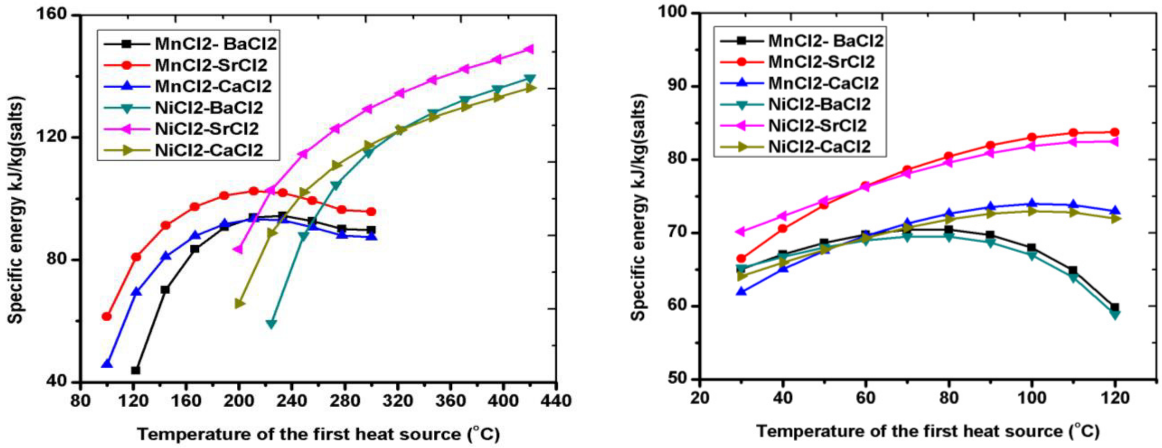


(a) (b)

Fig. 4. Evaluation of thermal efficiency under various heat source temperature
(a) Mode 1, recover the first heat source; (b) Mode 2, recover the second heat source

4.2 Evaluation of specific energy

In order to form a low weight and high power generation capacity system, the specific energy of the system using six chemisorption working pairs are evaluated and compared as shown in Fig. 5. Results indicated the system using $SrCl_2$ has the highest specific energy compared with other working pairs. The highest specific energy of $MnCl_2$-$SrCl_2$ is about 102 kJ/kg(salts) when the first heat source temperature is around 210 °C. $NiCl_2$-$SrCl_2$ has the highest specific energy when the heat source temp lower than 60 °C and $MnCl_2$-$SrCl_2$ has the best specific energy when source temperature ranging from 60 °C to 120 °C when the system is in Mode 2. The highest specific energy of the Mode 2 of the system is around 85 kJ/kg(salts) when $MnCl_2$-$SrCl_2$ is the working pair under the second heat source temperature from 100 to 120 °C.



(a) (b)

Fig. 5. Evaluation of specific energy under various heat source temperature
(a) Mode 1, recover the first heat source; (b) Mode 2, recover the second heat source

4.3 Evaluation of rotational speed

The rotational speed of the scroll expander under per kW supplied heat of Mode 1 and Mode 2 are studied to select the optimal operational conditions of the scroll device under various heat ratios and heat source temperature conditions. Results indicated the suitable heat source temperature for $MnCl_2$ and $NiCl_2$ as HTS is about 160 °C and 260 °C, respectively. $BaCl_2$ is preferred to be used as LTS in Mode 2 for ultra-low temperature heat recovery when the heat source temperature is around 60 °C. The system using $SrCl_2$ as LTS possesses the highest rotational speed under the same working conditions compared with other working pair candidates.

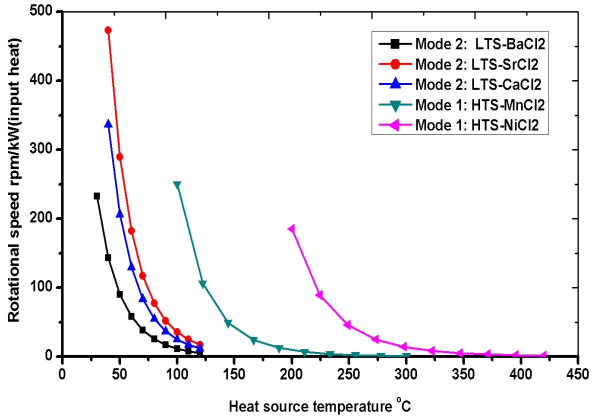


Fig. 6. Rotational speed of the scroll expander under per kw heat input

5. Conclusions

This paper reports the study on a novel dual-source chemisorption power generation system using scroll expander. The performance evaluation including thermal efficiency, specific energy and rotational speed of per kW heat input were conducted in order to identify the optimal operational conditions of the system using different chemisorption working pairs. Conclusions drawn from this study are

1. The thermal efficiency of Mode 1 is about 10% when $MnCl_2$-$SrCl_2$ servers as the working pair under the heat source temperature from 160 to 180 °C. When the first heat source is higher than 320 °C, $NiCl_2$-$SrCl_2$ is suitable to be used with the overall thermal efficiency at 8% in Mode 1. When the second heat source temperature is lower than 80 °C, $BaCl_2$ can achieve the highest thermal efficiency of Mode 2 among other LTS candidates with the average thermal efficiency at 12%. When $SrCl_2$ is used to recover the second heat source, the overall thermal efficiency of Mode 2 is about 11% under the driven heat source temperature from 80 to 120 °C.

2. The analysis of the specific energy of the system indicated that $MnCl_2$-$SrCl_2$ achieves the highest specific energy at 102 kJ/kg(salts) under the first heat source temperature at 210 °C. The highest specific energy obtained from Mode 2 is around 85 kJ/kg using $MnCl_2$-$SrCl_2$ as the working pair under the second heat source temperature from 100 to 120 °C.

3. The results obtained from the evaluation of the rotational speed of the scroll device pointed out the suitable first heat source supplied to $MnCl_2$ and $NiCl_2$ as HTS is about 160 and 260 ^{o}C, respectively. When the system is required to recover ultra-low temperature heat source in Mode 2, $BaCl_2$ is preferred to be used.

4. Considering about the thermal efficiency, specific energy and rotational speed of the scroll device, $MnCl_2$-$SrCl_2$ is recommended to be used in the system under the first heat source temperature from 180 to 200 ^{o}C and second heat source temperature from 80 to 90 ^{o}C.

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Biography

Dr Yiji Lu, born in June 1989, is currently a research associate in Newcastle University. He graduated from Shanghai Jiao Tong University in 2011 for his bachelor degree, he conducted his M.Phil. and Ph.D. in Newcastle University in 2012 and 2016. His Ph.D. program was fully sponsored by EPSRC and was awarded the '2015 Chinese Government Award for Outstanding Self-financed Students Abroad' from China Scholarship Council. His research interests include but not limited to advanced waste heat recovery technologies, engine thermal management, chemisorption cycles and expansion machines for power generation system. He has been regularly invited to review the manuscripts for the scientific journals including Applied Energy, Applied Thermal Engineering, Energy (the international Journal), and Energy for Sustainable Development.