Performance Improvement of a Combined Double-Way Thermochemical Sorption Refrigeration Cycle with Reheating Process

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A reheating process is proposed aimed at improving the system performance of a combined double-way thermochemical sorption thermodynamic cycle based on adsorption and resorption refrigeration. The reheating process causes an increase in the driving equilibrium temperature difference, which promotes the reaction rate and thus improves the global conversion of sorbent. Experimental results showed that the proposed reheating process is an effective technique for improving the performance of the combined double-way cycle. The improvement in the COP ranged between 12 and 48% in the different cycle conditions, when compared with the combined double-way cycle without reheating. The low pseudo-evaporation temperature and high heat sink temperature can further improve the system performance. The COP obtained with the combined double-way cycle without reheating was 0.57, when the heat sink, evaporation, and pseudo-evaporation temperatures were 25, 10, and 10°C, respectively. However, at the same cycle conditions, the COP increased to 0.64 when the proposed reheating process was introduced in the combined double-way sorption cycle.

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Introduction

Research and development of solid–gas sorption refrigeration machines has been going on for more than 50 years. These systems have the potential to reduce the primary energy consumption and can contribute toward the global sustainable development. The operation principle of sorption systems is based on the thermal effects of reversible physicochemical reactions between sorbents and refrigerants.[1] These heat-powered green refrigeration technologies have received more and more attention in the recent years because they have a large energy saving potential and are environmental friendly.[2] However, solid sorption refrigeration systems have not been applied extensively on the market due to its low system performance in terms of coefficient of performance (COP).

Conventional adsorption refrigeration systems based on the evaporation process have been widely studied, and some of these machines have already been commercialized. For these systems, the useful cooling is produced by the vaporization heat of the refrigerant during the adsorption phase. For thermochemical sorption refrigeration systems based on the resorption process, the useful cooling can also be obtained from the decomposition reaction heat of a reactive salt at a low temperature. In this type of system, the evaporator is replaced by a solid–gas reactor, and the reaction heat consumed during the decomposition reaction phase of the reactor is employed to provide the useful cooling-effect.

For solid sorption refrigeration systems, to become more competitive to the conventional vapor compression refrigeration devices, it is necessary to develop some specific techniques to improve their working performance. These

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techniques may include the utilization of better sorption materials, enhancement of heat and mass transfer in the reactive beds. and the development of advanced sorption thermodynamic cycles.[3] Heat management and mass recovery strategies have been widely used to improve the system performance by reducing the heat consumption and increasing the cycled mass of the refrigerant, respectively. Some of the typical sorption thermodynamic cycles include the thermal wave cycle,[4] forced convection cycle,[5] mass recovery cycle,[6] cascading cycle,[7] multi-stage cycle,[8] mass and heat recovery cycle,[9,10] sorption cycle with heat pipe thermal control,[11,12] double-effect sorption cycle,[13,14] double-effect resorption cycle,[1,15] and so on. Recently, Li et al. [16] developed a multi-mode, multi-salt, and multi-effect thermochemical sorption refrigeration cycle to further improve COP by combining internal heat recovery strategy, adsorption refrigeration process, and resorption refrigeration process. In this system, four reactors were filled with three different reactive salts, and the synthesis reaction heat of a high-temperature salt was recovered and used to supply the decomposition reaction heat of a middle-temperature salt. The predicted COP for this advanced sorption cycle was higher than 1.

Later, the feasibility of the proposed innovative double-way sorption thermodynamic cycle was experimentally verified using a simple test unit.[17] Experimental results showed that the advanced combined double-way thermodynamic cycle is feasible for refrigeration application, in which both the adsorption refrigeration and the resorption refrigeration processes were combined to produce the useful cooling. The combined double-way sorption cycle has a higher COP compared with the convectional adsorption cycle and the resorption cycle. However, analysis of experimental data indicated that the combined double-way thermodynamic cycle still had a major shortcoming of low global conversion due to the low reaction rate during the resorption phase.

In this article, a reheating process is proposed to improve the global conversion in the combined double-way thermochemical sorption thermodynamic cycle. The heat required during the reheating process is supplied by cooling water at ambient temperature, thus, no additional heat input from an external high-temperature heat source is required during this operating period. A simple experimental test unit was used to investigate the cycle characteristics and the performance of the proposed combined double-way sorption thermodynamic cycle with reheating process.

Working Principle and Thermodynamic Analysis of the Combined Double-Way Thermochemical Sorption Cycle with Reheating Process

The schematic diagram of the combined double-way thermochemical sorption thermodynamic cycle is shown in Figure 1. It mainly consists of a solid–gas reactor 1, a solid–gas reactor 2, a condenser, and an evaporator, whereby Q_{cond} is the condensation heat of refrigerant, Q_{evap} is the evaporation heat of refrigerant, Q_{des1} is the decomposition reaction heat of reactor 1, and Q_{ads2} is the synthesis reaction heat of reactor 2. To accomplish adsorption and resorption refrigeration processes simultaneously, two different reactive salts were used in the two solid–gas reactors. The high-temperature salt (HTS) filled in reactor 1 has a higher equilibrium temperature than the low-temperature salt (LTS) filled in reactor 2 at the same operating pressure.

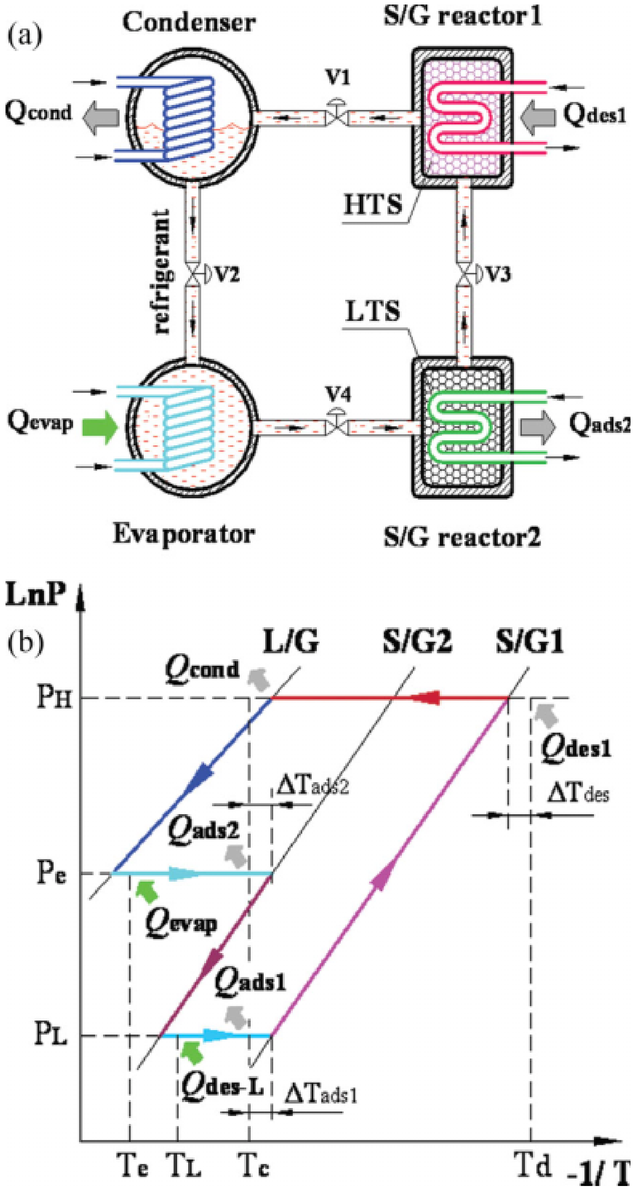

Figure 1. Schematic diagram of a combined double-way thermochemical sorption refrigeration cycle.

(a) Operating principle and (b) Clapeyron diagram. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

The working mode of the double-way sorption cycle can be divided into two phases. During the first phase, the HTS in reactor 1 is heated by an external heat source to desorb the refrigerant to the condenser. At the same time, the LTS in reactor 2 is cooled by a heat sink to adsorb the refrigerant from the evaporator. The evaporation heat of the refrigerant produces the first cooling-effect. In the second phase, a resorption process occurs between the HTS and the LTS, and the refrigerant gas is transferred from reactor 2 to reactor 1 due to the driving pressure drop. The reaction heat during the decomposition reaction process of the LTS produces the second cooling-effect. These two cold productions can be obtained during one cycle at the expense of only one high-temperature heat input into the HTS reactor. A detailed

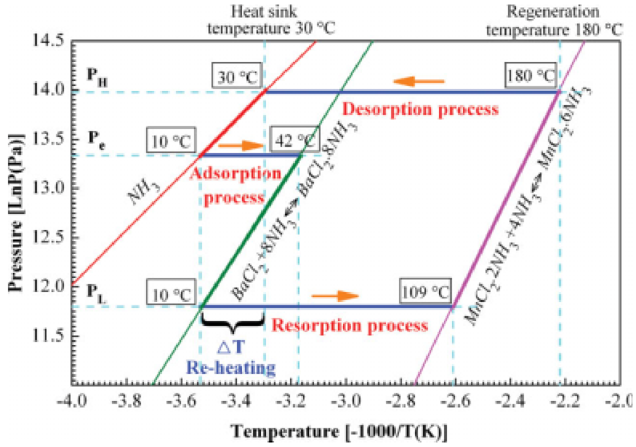

Figure 2. Working principle of the combined double-way sorption thermodynamic cycle with reheating process.

[Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

description of the working mode of the combined double-way thermochemical sorption thermodynamic cycle has been presented in the literature.[17]

Figure 2 shows the working principle of the combined double-way sorption thermodynamic cycle with reheating process, in which $MnCl_2$ and $BaCl_2$, were used as the high-temperature salt (HTS), the low-temperature salt (LTS), respectively, whereas NH_3 was the refrigerant. The solid–gas equilibrium lines of the two reactive salts and the liquid–vapor equilibrium line of ammonia were obtained from the Clausius-Clapeyron equation:

$$\mathrm{Ln}\left(\frac{P_{eq}}{P^{o}}\right) = -\frac{\Delta H_R}{RT_{eq}} + \frac{\Delta S}{R} \tag{1}$$

where P_{eq} is the equilibrium pressure (Pa), P^{o} is the reference pressure (1×10^5 Pa), ΔH_R is the enthalpy of transformation ($\mathrm{kJ \cdot mol^{-1}}$), ΔS is the entropy of transformation ($\mathrm{kJ \cdot mol^{-1} \cdot} K^{-1}$), R is the universal gas constant ($\mathrm{kJ \cdot mol^{-1} \cdot} K^{-1}$), T_{eq} is the equilibrium temperature (K).

The operation of the combined double-way thermochemical sorption refrigeration cycle is based on the following reactions:

During the adsorption refrigeration phase:

$$\begin{cases} \mathrm{BaCl_2 + 8NH_3 \Leftrightarrow BaCl_2 \cdot 8NH_3} + \Delta H_{RL} \\ \quad \Delta H_{RL} = 36.2\ \mathrm{kJ \cdot mol^{-1}} \\ \mathrm{NH_3(gas) \Leftrightarrow NH_3(liq)} + \Delta H_{evap} \end{cases} \tag{2}$$

During the resorption refrigeration phase:

$$\begin{cases} \mathrm{BaCl_2 + 8NH_3 \Leftrightarrow BaCl_2 \cdot 8NH_3} + \Delta H_{RL} \\ \quad \Delta H_{RL} = 36.2\ \mathrm{kJ \cdot mol^{-1}} \\ \mathrm{MnCl_2 \cdot 2NH_3 + 4NH_3 \Leftrightarrow MnCl_2 \cdot 6NH_3} + \Delta H_{RH} \\ \quad \Delta H_{RH} = 46.6\ \mathrm{kJ \cdot mol^{-1}} \end{cases} \tag{3}$$

where ΔH_{evap} is the evaporation enthalpy of ammonia ($\mathrm{kJ \cdot mol^{-1}}$), ΔH_{RL} is the reactive enthalpy of $BaCl_2$ ($\mathrm{kJ \cdot mol^{-1}}$), ΔH_{RH} is the reactive enthalpy of $MnCl_2$ ($\mathrm{kJ \cdot mol^{-1}}$).

The working process of the combined double-way sorption thermodynamic cycle is constrained by three levels of pressure: high pressure (P_H) during the decomposition reaction process of $MnCl_2$, middle pressure (P_e) during the adsorption refrigeration phase based on the evaporation process, and low pressure (P_L) during the resorption refrigeration phase. The reaction rate is dependent on the equilibrium temperature difference between the constraint temperature (T_c) and the equilibrium temperature (T_{eq}) during the chemical reaction processes.[18] The higher the equilibrium temperature difference, the faster the chemical reaction rate.

As illustrated in Figure 2, the refrigerant is transferred from the LTS reactor to the HTS reactor during the resorption refrigeration process. In this process, the LTS reactor is heated by a heat transfer fluid at a low-temperature of 10°C to desorb the refrigerant to the HTS reactor. Subsequently, the working modes of the two reactors are interchanged, and the LTS is cooled by a heat sink fluid at a temperature of 30°C to adsorb the refrigerant from the evaporator during the adsorption refrigeration process. For the combined double-way sorption thermodynamic cycle without reheating process, the LTS reactor is changed from decomposition reaction mode to synthesis reaction mode once the resorption refrigeration process is completed.

For the proposed combined double-way sorption thermodynamic cycle with reheating process, a reheating process was performed at the end of the resorption phase just before the beginning of the adsorption process. In this case, the LTS reactor is reheated by replacing the low-temperature heat transfer fluid with a relatively higher-temperature heat sink fluid. The increase in the driving temperature difference ΔT causes an increase in the reaction rate. This results to a higher mass of the refrigerant being transferred from the LTS reactor to the HTS reactor during the resorption phase. Furthermore, it implies that the LTS reactor will in turn adsorb a higher mass of ammonia during the next adsorption phase. Thus, the global conversion and the cycled mass of the refrigerant in the combined double-way thermodynamic cycle can be improved by the reheating process.

Experimental Test Unit

A simple experimental test unit was set up to evaluate the performance of the combined double-way sorption thermodynamic cycle with reheating process. The schematic diagram and the photograph of the experimental test unit are shown in Figures 3 and 4, respectively. The test unit consisted mainly of a high-temperature reactor (HTS reactor), a low-temperature reactor (LTS reactor), a condenser/evaporator, and a data acquisition setup. The HTS reactor, the LTS reactor, and the condenser/evaporator were placed in an oil jacket, a water jacket, and an ethanol jacket, respectively. All the jackets were insulated to reduce the heat losses to the ambient.

During the decomposition reaction phase of the HTS reactor, the decomposition heat was provided by the high-temperature oil from an electric-powered oil boiler. The synthesis reaction heat rejected by the HTS reactor during the resorption phase was transferred to the cooling water in an oil–water heat exchanger. For the LTS reactor, the decomposition reaction heat consumed by the LTS during the

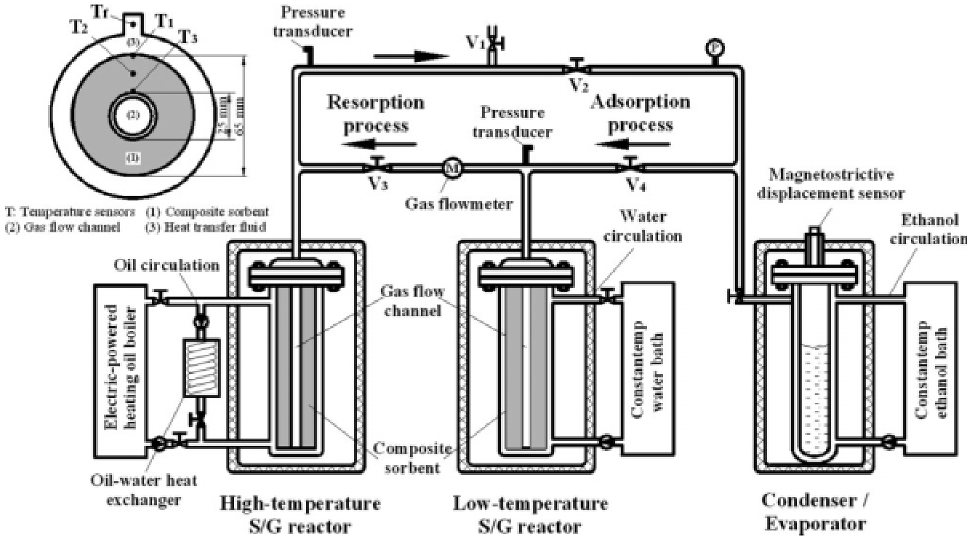

Figure 3. Schematic diagram of the experimental test unit and the arrangement of temperature sensors.

resorption process produced useful cooling, and the reaction heat released by the LTS during the synthesis reaction process was removed by the cooling water.

A magnetostrictive displacement sensor positioned in the evaporator/condenser was used to measure the amount of refrigerant consumed by the LTS and that desorbed by the HTS. The relative measuring error of the sensor was less than 0.05%. The cycled mass of the refrigerant consumed or desorbed by the sorbents was calculated using the following equation:

$$\mathrm{m_{ad}}(t) = -\frac{\rho(T_e)\, A_{\mathrm{Ev}}\, [L(t) - L(t_0)]}{\mathrm{m_S}} \tag{4}$$

where $\mathrm{m_{ad}}(t)$ is the amount of ammonia consumed by reactive salt $\mathrm{kg_{NH_3}} \cdot \mathrm{kg_{salt}^{-1}}$; $\rho(T_e)$ is the density of liquid ammonia at evaporation temperature $\mathrm{kg{\cdot}m^{-3}}$; A_{Ev} is the cross-section area of the evaporator $\mathrm{m^2}$; $L(t)$ and $L(t_0)$ are the liquid level (m) inside the evaporator during the synthesis phase and at the beginning of the synthesis reaction, respectively.

To avoid the agglomeration phenomenon of the pure salt powders and to enhance the heat and mass transfer of the sorbents, expanded graphite was used as an inert porous additive due to its high thermal conductivity and gas permeability [19–22]. In addition, a consolidation process was performed during the manufacture of the composite sorbents to further improve the heat transfer. The composite sorbents made from salt and expanded graphite had a graphite mass ratio equal to 0.5, and they were compressed to form cylindrical blocks with density equal to 250 $\mathrm{kg{\cdot}m^{-3}}$. The scanning electron microscopy (SEM) image of expanded graphite and consolidated composite sorbent showed that the pure salt powders were uniformly distributed in the expanded graphite matrix, and this implied that chemical reaction could take place at all portions of the composite material. The consolidated compounds of $MnCl_2$-expanded graphite and $BaCl_2$-expanded graphite were filled in the HTS reactor and LTS reactor, respectively.

Three temperature sensors (four-wire PT100 platinum type) at different radii were employed to evaluate the transient heat transfer of each reactive composite sorbent during the synthesis reaction and the decomposition reaction phases. The temperature measurement error was ±0.19°C. Two pressure transducers with an accuracy of 1.5% were used to measure the operating pressures of the reactors.

Results and Discussion

Temperature evolution of the LTS reactor with $BaCl_2$

For a conventional sorption refrigeration cycle, the temperature evolution of the reactor with $BaCl_2$ is shown in Figure 5. During the synthesis reaction phase, the reactor was cooled by a heat sink as it consumed the refrigerant from the evaporator. The cold production resulted from the evaporation heat of the refrigerant inside the evaporator. During the decomposition reaction mode, the reactor was

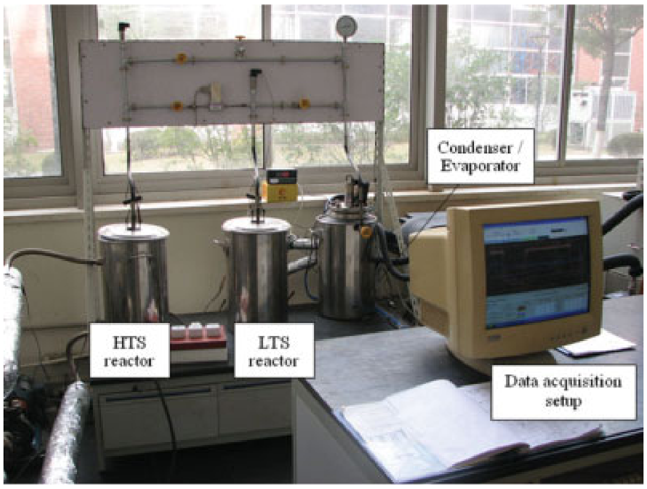

Figure 4. Photograph of the experimental test unit for the combined double-way sorption cycle.

[Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

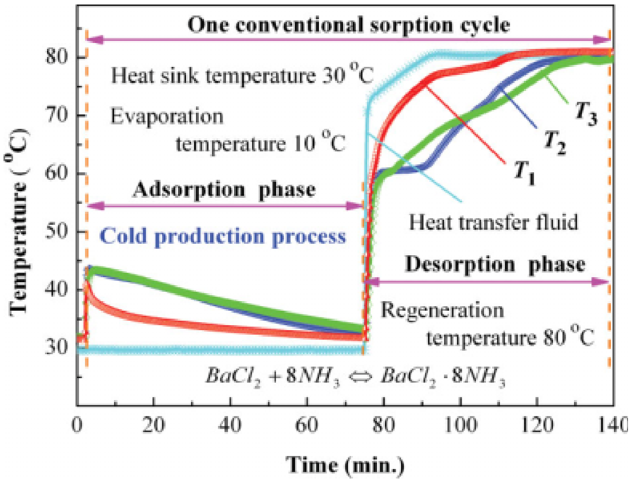

Figure 5. Temperature evolution of the reactor with $BaCl_2$ during one conventional sorption refrigeration cycle.

[Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

heated by an external heat source to desorb the refrigerant to the condenser. It was observed that the reactor temperature during the synthesis reaction phase was much lower than that during the decomposition reaction phase due to pressure constraints. The operating pressure during the synthesis reaction phase was about 5.9 bar, whereas during the decomposition reaction phase, it was about 12.1 bar, when the evaporation and condensation temperatures for the two working phases were 10 and 30°C, respectively.

Figure 6 shows the temperature evolution of the LTS reactor with $BaCl_2$ in the combined double-way sorption thermodynamic cycle with reheating process. The temperature evolution for this double-way cycle was distinctly different from that of the conventional sorption refrigeration cycle as given in Figure 5. In the presented double-way sorption thermodynamic cycle, both the adsorption refrigeration and resorption refrigeration processes were combined to produce useful cooling. A reversible physicochemical reaction between barium chloride and ammonia, as described by Eq. 2, took place during the adsorption and resorption refrigeration phases.

During the synthesis reaction phase, the reactor temperature increased rapidly at the beginning of the phase due to a large amount of reaction heat released during the exothermic synthesis reaction from $BaCl_2$ to $BaCl_2 \cdot 8NH_3$. This phenomenon implied that the synthesis heat could not be removed fast enough by the heat transfer fluid. As the synthesis reaction progressed, the conversion rate decreased and the reaction heat reduced. Once the amount of the reaction heat released was lower than that which could be removed by the heat transfer fluid, the reactor temperature started to decrease until it reached a temperature close to the heat transfer fluid temperature. Moreover, it was observed that the changing patterns of transient temperature at the different radii in the composite sorbent were different. The temperature (T_1) near the wall of the reactor was lower than that closer to the gas channel (T_3) due to the heat transfer constraint. It seemed that the reaction closer to the heat exchanger wall could reach completion earlier than that at the other portions of the composite material. The first cold production resulted from the evaporation heat of the refrigerant inside evaporator.

During the resorption phase, the LTS reactor worked as a pseudo-evaporator as decomposition reaction occurred. In this phase, the reaction heat consumed by the sorbent during the decomposition reaction from $BaCl_2 \cdot 8NH_3$ to $BaCl_2$ produced a useful cooling effect. The regeneration temperature of the LTS was referred to as ‘pseudo-evaporation temperature’. It was observed that the LTS reactor, initially underwent a precooling mode, whereby the decomposition reaction heat of the LTS firstly removed the sensible heats of the metallic part of the reactor and the composite sorbent. Subsequently, the decomposition reaction heat started to produce useful cooling when the reactor temperature was lower than the temperature of heat transfer fluid.

The temperature of the LTS decreased rapidly at the beginning of the resorption process. The abrupt reduction of temperature observed during the precooling process implies that a large amount of decomposition reaction heat was consumed by the reactive salt, which can be attributed to the prompt transfer of ammonia from the LTS reactor to the HTS reactor. It also means that the reaction heat consumed was higher than the heat supplied by the heat transfer fluid at that period. Thereafter, the reactor temperature was fairly constant as the decomposition reaction progressed, which implies that the amount of heat consumed by the LTS was almost similar to the heat input supplied by the heat transfer fluid. Later, the reactor temperature gradually increased as the amount of heat consumed decreased. The second cold production was obtained from the reaction heat consumed by the LTS during the decomposition reaction from $BaCl_2 \cdot 8NH_3$ to $BaCl_2$.

At the end of the resorption phase, a reheating process (Figure 6) was performed to increase the cycled mass of the refrigerant. In this case, the heat transfer fluid was switched from the pseudo-evaporation temperature of 10°C to the cooling water temperature of 30°C. Consequently, a prompt increase in the reactor temperature was observed during the reheating process. The high equilibrium temperature difference ΔT enhanced the reaction rate and thus improved the global conversion. Furthermore, during the next double-way

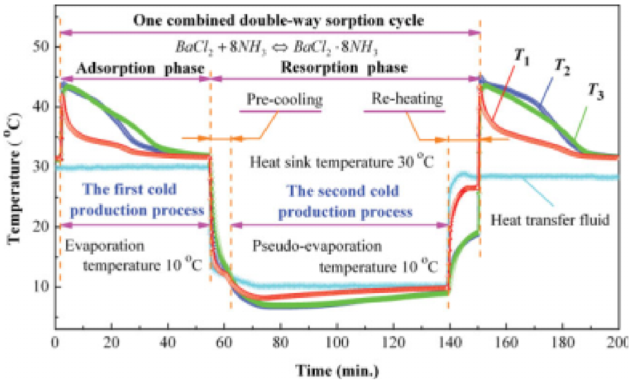

Figure 6. Temperature evolution of the LTS reactor with $BaCl_2$ during one combined double-way sorption cycle with reheating process.

[Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

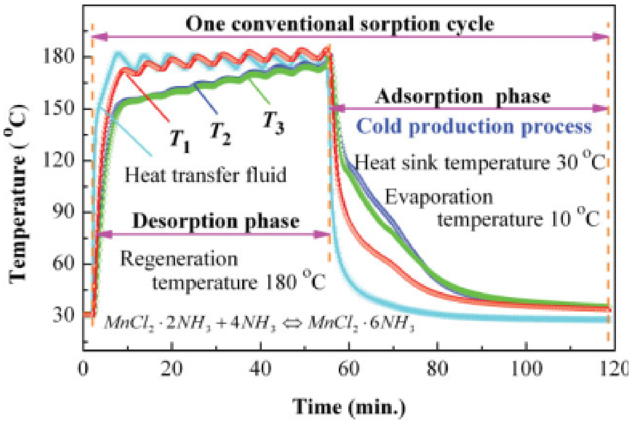

Figure 7. Temperature evolution of the reactor with $MnCl_2$ during one conventional sorption refrigeration cycle.

[Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

sorption cycle, when the LTS reactor mode was interchanged to synthesis reaction mode, a higher mass of the refrigerant could be consumed by the LTS from the evaporator. Therefore, the system performance would be improved by the proposed reheating process.

When the temperature evolutions during the synthesis reaction phase and the decomposition reaction phase (also called as resorption refrigeration phase) were compared, it was found that the resorption phase had a longer cycle time than the synthesis reaction phase, despite the fact that the LTS reacted with similar amount of ammonia in both operating phases. This difference in the cycled time shows that reaction rate during the former phase was lower than that during the latter phase, which can be attributed to the difference in Δ*P* between the constraint pressure and the equilibrium pressure during the two working phases.

Temperature evolution of the HTS reactor with $MnCl_2$

The temperature evolution of the reactor with $MnCl_2$ is shown in Figure 7 when it was operated with the conventional sorption refrigeration cycle. During the decomposition reaction phase, the reactor was heated by an electric-powered oil boiler to desorb the refrigerant to the condenser. During the synthesis reaction phase, the reactor was cooled by a heat sink to adsorb the refrigerant from the evaporator. A distinct reaction plateau was observed during the adsorption refrigeration phase, whereby the reactor temperature remained almost constant for several minutes. This phenomenon implies that the reaction from $MnCl_2{\cdot}2NH_3$ to $MnCl_2{\cdot}6NH_3$ occurred and the amount of heat released by the synthesis reaction was almost equal to that removed by the heat transfer fluid.

Figure 8 shows the temperature evolution of the HTS reactor with $MnCl_2$ when it was operated with the combined double-way sorption thermodynamic cycle with reheating process. During the decomposition phase, the reactor temperature increased with the increase in the heat transfer fluid temperature, and the reaction heat required by the HTS was supplied by the heat transfer fluid. A high temperature difference between the inner and the outer parts of the composite sorbent was observed due to the heat transfer constraint. In addition, the oscillation in the reactor temperature observed was caused by a low accuracy of the thermostat controller in the oil boiler.

During the synthesis phase of the HTS; also referred as resorption refrigeration phase, the HTS reactor was cooled by a heat sink to adsorb the refrigerant from the LTS reactor. It can be seen that the temperature evolution was very smooth. Unlike the temperature evolution during the synthesis reaction phase as shown in Figure 7, the obvious reaction plateau did not occur in Figure 8 during the resorption refrigeration phase before the implementation of the proposed reheating process. This implies that the amount of reaction heat released by the HTS during the synthesis reaction from $MnCl_2{\cdot}2NH_3$ to $MnCl_2{\cdot}6NH_3$ was lower than that removed by the heat transfer fluid, thus the synthesis heat could be removed timely by the heat sink. This is because the cycled mass of the refrigerant is dependent on both the decomposition rate of the LTS and the synthesis rate of the HTS in the combined double-way sorption cycle, whereas it is only dependent on the synthesis rate of the HTS in the conventional sorption cycle.

As shown in Figure 8, there was a sudden increase in the HTS reactor temperature during the reheating process. This indicates a large amount of synthesis heat was released promptly at that period, which could not be removed fast enough by the heat sink. The heat released resulted from a large mass of ammonia being transferred from the LTS reactor to the HTS reactor during the reheating process. Thus, the cycled mass quantity of the refrigerant in the combined double-way sorption thermodynamic cycle with reheating was enhanced when compared with that in the combined double-way sorption thermodynamic cycle without reheating process.

Pressure evolution during the resorption refrigeration phase

The pressure evolution of the HTS and the LTS reactors during the resorption phase is shown in Figure 9. Synthesis reaction occurred in the HTS reactor, whereas decomposition reaction took place in the LTS reactor in accordance with Eq. 3. It was observed that the working pressure decreased

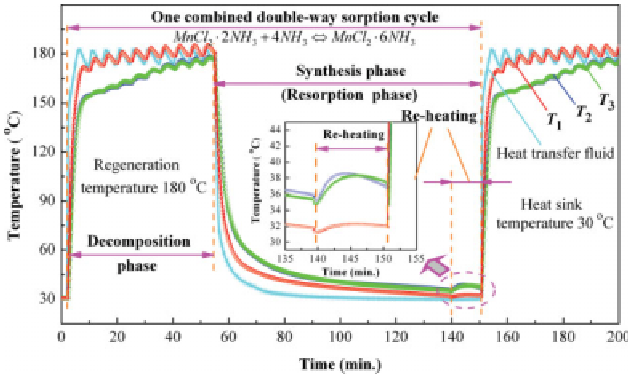

Figure 8. Temperature evolution of the HTS reactor with $MnCl_2$ during one combined double-way sorption cycle with reheating process.

[Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

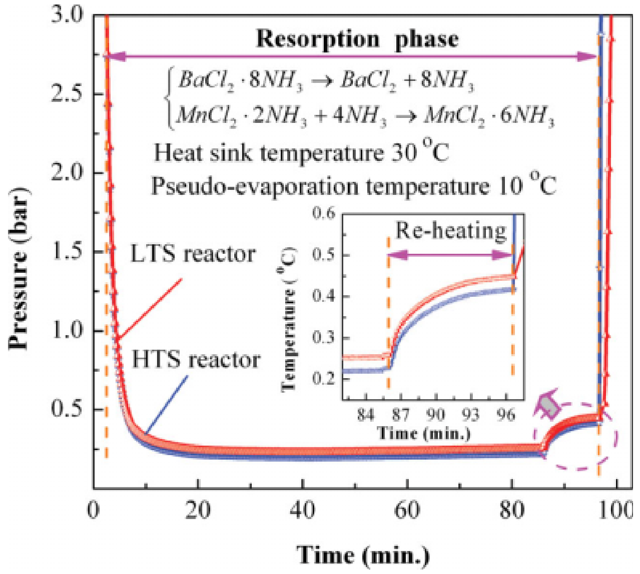

Figure 9. Pressure evolution during the resorption phase of the combined double-way sorption cycle with reheating process.

[Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

rapidly during the first few minutes of the reaction process, after which it remained approximately constant as the reaction progressed. Such a pressure evolution suggests that the synthesis rate of the HTS was higher than the decomposition rate of the LTS at the beginning of the resorption phase. This is because the pressure evolution was strongly influenced by the amount of the gas that was simultaneously desorbed by the LTS reactor and consumed by the HTS reactor. The stabilization of pressure occurred when the amount of ammonia desorbed by the LTS in decomposition reaction was similar to the amount consumed by the HTS in synthesis reaction.

At the end of the resorption phase, a reheating process was introduced, and the pressure of the two reactors went up due to the increase in the amount of gas generated during the reheating process. This indicated that the decomposition rate of the LTS was higher than the synthesis rate of the HTS at that moment, and the gas desorbed from the LTS could not be consumed timely by the HTS. This observation further supports the conclusion that the cycled mass of ammonia can be effectively improved by the proposed reheating process.

Performance improvement of the combined double-way sorption thermodynamic cycle with reheating process

The system performance of the combined double-way sorption thermodynamic cycle was evaluated at different heat sink temperatures, evaporation temperatures, and pseudo-evaporation temperatures (Table 1). The useful cooling obtained resulted from the evaporation heat of the refrigerant during the adsorption refrigeration and the decomposition reaction heat of the LTS during the resorption refrigeration. The exact equations used for the calculation of the COP of the combined double-way sorption refrigeration cycle were presented in Ref. 17.

It can be observed in Table 1 that the system performance was improved significantly by the introduction of the proposed reheating process. The improvement in the COP ranged between 12 and 48% according to the different experimental conditions, when compared with the combined double-way sorption thermodynamic cycle without reheating.

For a given heat sink temperature, the lower the evaporation temperature and pseudo-evaporation temperature, the higher the performance improvement. For example, when the heat sink temperature was 25°C, the COP increased by 12% at the evaporation and pseudo-evaporation temperatures of 10°C, whereas it reached 28% at the evaporation and pseudo-evaporation temperatures of 5°C. This can be attributed to the different driving equilibrium temperature difference between the constraint temperature and the equilibrium temperature. For the same heat sink temperature, a lower pseudo-evaporation temperature means a higher equilibrium temperature difference during the reheating process. Thus, the transferred mass of the refrigerant was larger because the reaction rate is proportional to the driving equilibrium difference.

Moreover, it was found that the heat sink temperature has a strong influence on the performance improvement. The higher the heat sink temperature, the higher the performance improvement for a given evaporation and pseudo-evaporation temperatures. For example, when the evaporation and pseudo-evaporation temperatures were 10°C, the COP increased by 12% at the heat sink temperature of 25°C, whereas it was as high as 48% at the heat sink temperature of 30°C. The higher heat sink temperature resulted to a higher driving temperature difference, and hence higher reaction rate during the reheating process, thus, the conversion rate was improved.

It can be seen that the COP obtained with the combined double-way sorption thermodynamic cycle without reheating was about 0.57 at the heat sink temperature of 25°C, evaporation and pseudo-evaporation temperatures of 10°C. The COP reached about 0.64 when the proposed reheating process was introduced in the combined double-way sorption thermodynamic cycle. However, the obtained COP was still much lower than the theoretical maximum COP of 1.24[17] due to a large proportion of thermal capacity of the metallic part of reactor in the simple experimental test unit.

Table 1. Performance Improvement of the Combined Double-Way Sorption Cycle by Using Reheating Process

Cooling Water Temperature T_c (°C)	Evaporation Temperature, T_e (°C)	Pseudo-Evaporation Temperature, T_{pe} (°C)	Without Reheating, COP_1	With Reheating, COP_2	Improvement Range, Δ%
25	5	5	0.31	0.4	28
	10	10	0.57	0.64	12
30	10	10	0.32	0.48	48
	15	15	0.42	0.56	34

Conclusion

In this article, a reheating process is proposed to improve the system performance of a combined double-way thermochemical sorption thermodynamic cycle based on adsorption and resorption processes. Analysis of experimental data showed that the reaction rate during the resorption refrigeration phase was lower than that during the adsorption refrigeration phase due to the different driving equilibrium difference. A reheating process was introduced at the end of the resorption refrigerant phase and it caused an increase in the driving equilibrium temperature difference, which could enhance the reaction rate and thus improve the global conversion of the sorbents.

Experimental results showed that the system performance can be improved significantly by using the proposed reheating process when compared with the combined double-way sorption thermodynamic cycle without reheating. Moreover, low pseudo-evaporation temperature and high heat sink temperature can further improve the system performance. The improvement in the COP varied from 12 to 48% according to the different constraint conditions. The COP obtained with the combined double-way sorption thermodynamic cycle without reheating was about 0.57 at the heat sink temperature of 25°C, evaporation temperature of 10°C, and pseudo-evaporation temperature of 10°C. However, it could reach about 0.64 when the proposed reheating process was introduced in the combined double-way sorption thermodynamic cycle. The proposed reheating process is an effective technique which can be used to improve the system performance of the combined double-way thermochemical sorption thermodynamic cycle.

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