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Experimental investigation on an innovative resorption system for energy storage and upgrade

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Abstract: Progress of efficient thermal energy storage (TES) has become a key technology for the development of energy conversion system. Among TES technologies, sorption thermal energy storage (STES) has drawn burgeoning attentions due to its advantages of high energy density, little heat loss and flexible working modes. Based on STES, this paper presents an innovative resorption sorption energy storage (RTES), and the experimental system is established and investigated for energy storage and upgrade. 4.8 kg and 3.9 kg MnCl_2 and CaCl_2 composite sorbents are separately filled in the sorption reactor, and expanded natural graphite treated with sulfuric acid (ENG-TSA) is integrated as the matrix for heat transfer intensification. It is indicated that the highest energy storage density are 662 kJ/kg and 596 kJ/kg when heat input temperature is 125°C and heat release temperature are 130°C and 135°C, respectively. For different heat input and release temperature, the energy efficiency and exergy efficiency range from 27.5% to 40.6% and from 32.5% to 47%, respectively. The novel RTES system verifies the feasibility for energy storage and upgrade, which shows the great potential for low grade heat utilization especially for industrial process.

Keywords: Resorption; Composite sorbent; Energy upgrade; Energy storage density

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24 Nomenclature

c	Specific heat (kJ/(kg·°C))
COP	Coefficient of performance
E	Exergy (kJ/kg)
HSD	Heat storage density(kJ/kg)
HTS	High temperature salt
h	Enthalpy (kJ/kg)
LTS	Low temperature salt
m	Mass flow rate (kg/s)
P	Pressure (Pa)
Q	Heating (kJ)
R	Gas constant (J/(mol·K))
T	Temperature (°C)

25 Greek letters

ΔH	Enthalpy of sorbent
Δx	Sorption quantity variation (kg/kg)
ρ	Density of ammonia (kg/m ³)

26 Subscripts

E	Exergy
H	HTS reactor
h	Heat source
i	Theoretical
in	Input
L	LTS reactor
metal	Metallic part
NH ₃	Ammonia
Out	Release
r	Experimental
sorb	Sorbent
up	Upgrade

1. Introduction

In recent year, quite a lot of efforts have been made to improve energy conversion efficiency of renewable energy for realizing the low carbon future[1]. Among them, thermal energy storage (TES) technology has become one of the hot topics when considering efficient utilization of low grade heat, which is able to be obtained from solar power[2], industrial factories[3], and geothermal resource[4]. Generally speaking, TES can be commonly classified into three aspects, namely sensible heat energy storage, latent heat energy storage and thermochemical energy storage [5, 6].

Sensible heat energy storage relies on storing heat by temperature difference of the medium such as water, concrete and rock [7]. Latent heat energy storage depends on heat released and absorbed in the phase change process of phase change material(PCM) such as paraffin and nitrate[8]. Nonetheless, these two kinds of energy storage methods have the drawbacks of low energy densities, inapplicability for long distance and long time storage and unacceptable energy losses. Comparably, thermochemical energy storage can overcome these disadvantages by adjusting the time-discrepancy, space-discrepancy and instability between energy supplies and demands [9-11]. Based on the sorption and desorption processes, sorption thermal energy storage(STES) is considered as one attractive research field of thermochemical energy storage[6]. Energy is stored by breaking the binding force between the working fluid and the sorbent in term of chemical potential in the sorption process[12]. Various researchers investigated STES system by energy and exergy analysis due to its high efficiency of heat utilization[13]. Besides, STES has been regarded as a seasonal energy storage method with the advantages of small energy loss and high system compactness [14]. Under these scenarios, STES has drawn burgeoning attentions, and various researchers attempted to verify the feasibility of this innovative technology experimentally. Yu et al.[15] summarized different STES technologies driven by the solar energy, and comprehensively compared advantages and disadvantages of solid-gas working pairs. Li et al.[16, 17] analyzed sorption thermal battery based on solid-gas reaction process for solar cooling and heating energy storage and heat transformer. Results indicated that the highest heat and cold energy storage densities were 1600 kJ/kg and 720 kJ/kg, respectively for the working pair of $\text{SrCl}_2\text{-NH}_3$. Aydin et al.[18] investigated a novel sorption pipe reactor for solar thermal energy storage. Results demonstrated that a fourfold increase of absolute humidity difference of air could lead to approximately 2.3 times increment for average power output and an 8.8 times boost for average exergy.

Similar as STES, resorption process has also been considered to be applied for the TES

technology. This is mainly because pressure of the evaporator for ammonia STES system will be further increased if the higher heat release temperature is required. For example, when temperature of the evaporator is 58°C, the pressure of ammonia STES system will reach 2.5 MPa, which is over the limitation of normal safety valve. For resorption thermal energy storage (RTES), evaporator/condenser is replaced by a LTS reactor. An improved safety and system compactness can be guaranteed since there is no ammonia liquid in the system. Furthermore, quite a lot of working pairs can be selected for RTES[12]. Among them, working pair of $\text{MnCl}_2\text{-CaCl}_2\text{-NH}_3$ has been extensively investigated due to its good performance for the resorption refrigeration[19] and great potential for RTES[20]. Gao et al. [21] investigated the feasibility of a $\text{MnCl}_2\text{-CaCl}_2\text{-NH}_3$ sorption refrigerated truck driven by exhaust gas of engine. Results indicated that the highest cooling capacity and COP were able to reach 1.25 kW and 0.143 when the hot air and refrigerating temperature were 230°C and -5°C, respectively. Li et al.[22] analyzed this sorption working pair for energy storage and upgrade, and predicted its potential and high energy storage density. Our previous work has investigated the characteristics of $\text{MnCl}_2\text{-CaCl}_2\text{-NH}_3$ working pair for both direct heat supply [23] and combined heating and cooling[24]. Experimental results indicated that the largest energy storage density could reach 1706 kJ/kg when charging and discharging temperature were 160°C and 30°C, respectively. The maximum average cooling power achieved 1.07 kW during the discharging phase. The current researches on both STES and RTES mainly concentrated on the novel composite sorbent, thermodynamic cycle innovation and the sorption reactor optimization[25].

Nonetheless, energy upgrade is much different from the direct heat supply and combined heat and cooling, which provides more possibilities of releasing heat for both heat supplier and end user. Also noting that few experimental research work of RTES system has been launched, and especially for ammonia system which is rarely investigated for TES in real application. In this paper, an innovative $\text{MnCl}_2\text{-CaCl}_2\text{-NH}_3$ RTES system is established and investigated for energy storage and upgrade. The performance of energy upgrade is comprehensively compared with that of direct heat supply and combined heat and cooling.

2. Establishment of the RTES cycle for energy storage and upgrade

For RTES, there are commonly three working modes for different application occasions, which are direct heat supply, energy upgrade and combined heat and cooling supply[16]. This paper mainly

presents energy upgrade mode. Two working processes are included. One is the energy storage process and the other is the energy upgrade process. Fig.1 shows schematic diagram of energy storage and upgrade process. Fig.1a displays working mode whereas Fig.1b shows thermodynamic process. The energy storage process (A-B) lies in the desorption process of high temperature salt (HTS) reactor or sorption process of low temperature salt (LTS) reactor. As Fig.1b shows, when HTS reactor is heated by heat source with temperature T_{in} at point A, ammonia vapor which clings to sorbent starts to escape as the threshold binding force between working fluid and sorbent is exceeded. Ammonia vapor flows through a pipe and adsorbed by LTS reactor at a lower temperature level P_L . Sorption heat Q_{ads-L} is released to the surrounding environmental medium at point B. The low-grade thermal energy is stored in form of chemical bonds resulting from the desorption process between the HTS and LTS reactor.

When the energy storage process ends, HTS and LTS reactor are mutually separated. Energy upgrade process (B-C-D) starts which consists of isochoric heating process of LTS reactor (B-C) and desorption process of HTS reactor (C-D). The LTS reactor is heated by the heat source from point B to point C. The refrigerant will be desorbed by the LTS reactor at a high pressure P_H , and HTS reactor undergoes synthesis chemical reaction at point D. The sorption heat will be released for the end user with temperature T_{out} . As it is shown in Fig.1b, with the pressure lifting, the output temperature could be higher than the input temperature since the temperature is relevant with the pressure in solid-gas sorption reaction. The low grade heat is able to be upgraded from heat input temperature T_{in} to heat release temperature T_{out} . And the temperature lift magnitude is according to the Equation 1.

$$\Delta T = T_{out} - T_{in} \quad (1)$$

Fig. 1. Schematic diagram of energy storage and upgrade process (a) working mode; (b) thermodynamic processes.

Considering for both cycle sorption quantity and adaptability to the heat source temperature, $MnCl_2$ is selected as HTS while $CaCl_2$ is chosen as LTS for RTES system due to their good chemical and thermal stabilities[26, 27].

Fig.2 indicates the photo of RTES system for energy storage and upgrade. Six shell-tube vessels form sorption unit reactors, and HTS and LTS reactors are composed of three unit reactors, respectively. HTS sorption reactor is filled with 4.9 kg composite $MnCl_2$ while LTS sorption reactor is filled with 3.8 kg composite $CaCl_2$. The developing procedures of the composite sorbent can be referred to the reference[28]. Two PCM tanks as marked '1' in Fig.2a are installed to store the excess heat and cold which could achieve a goal of continuous refrigeration for combined heat and cooling mode. These two tanks are not concerned with the mode of energy storage and upgrade in this paper. Composite sorbents are impregnated with ENG-TSA as a mass ratio of 6:1 to develop the composite sorbent which is squeezed into the fin gaps of the finned tubes. The matrix of ENG-TSA is able to greatly improve the heat and mass transfer performance due to its porous structure[29]. As Fig.2a shows, RTES system mainly consists of an oil-water heat exchanger for cooling the HTS reactor, HTS and LTS reactors and several ammonia valves. Apart from the main RTES part, Fig.2b mainly demonstrates the auxiliary equipment, which includes a water thermostat, a cooling tower, an oil tank and a data collector. The oil tank controls the temperature of HTS sorption reactor. The water thermostat is used to control the temperature of LTS reactor. Since the water thermostat is used to control the temperature of LTS reactor, the real isochoric heating point is able to reach the point E with temperature T_r in Fig.1b which is lower than the T_{in} at point C. The heat release temperature will correspondingly decrease to point F with temperature $T_{r,out}$. This may decrease the heat release temperature, but it is still able to investigate the performance of RTES for the energy upgrade mode. In the experiment, the flowrate of the oil and water are about 1.4 m³/h and 0.9 m³/h, respectively. Pressure sensors (full scale from 0 to 2.5 MPa with tolerance of $\pm 0.1\%$) are placed at HTS and LTS reactor. Pt100 thermal resistance temperature sensors with 0.2% accuracy are adopted. The rest of experimental data are monitored and logged by an Agilent 34972A. Based on all the accuracies of measurement sensors, the calculation errors of mass energy density, COP_h (coefficient of performance) and exergy efficiency for RTES system are 4.5%, 5.6% and 5.8%, respectively.

(1) PCM energy storage tanks; (2) HTS reactor; (3) Oil-water heat exchanger for cooling HTS reactor; (4) LTS reactor; (5) Cooling tower; (6) Pressure relief valve; (7) Pressure gauge; (8) Inlet ammonia valve for power generation; (9) Ammonia valve connecting HTS with LTS reactor; (10) Outlet ammonia valve for power generation.

Fig. 2. Photo of RTES system (a) RTES part; (b) RTES system with auxiliary equipment.

To comprehensively investigate the performance of RTES system for energy storage and upgrade, different heat input and release temperature are adopted for comparison. The working processes involved in the experiment are as follows. First, the ammonia valve between HTS reactor and LTS reactor is open during the heat storage process. Afterwards ammonia valve is closed, HTS reactor is controlled to heat release temperature. Meanwhile, LTS reactor is heated to the higher temperature. In the experiment the LTS reactor is heated to 70°C or 80°C as the set temperature. Then the ammonia valve is open to supply the upgrade heat. Heat input temperature ranges from 125°C to 145°C with the increment of 5°C. Environmental temperature is around 20°C due to the winter condition. Heat release temperature ranges from 130°C to 150°C with the increment of 5°C if temperature of LTS reactor is heated to 70°C. When the temperature of LTS reactor is heated to 80°C, heat release temperature ranges from 135°C to 155°C. The reasons for selecting heat input and release temperature are as follows: Considering the environmental temperature, the theoretical desorption temperature of the HTS is about 80°C. As for the heat transfer temperature difference is 12°C, the lowest desorption temperature of HTS reactor is about 92°C. For this resorption system, the cycle sorption quantity is relatively low when the heat source temperature is below 120°C, which cannot realize the obvious temperature increment. Also noting that it is desirable that the largest heat release temperature increment should be higher than 2°C

due to temperature testing error of 0.2°C. 10°C temperature lift for RTES system is reasonable to explain the characteristics of energy upgrade, and 5°C temperature lift is also adopted for comparison.

3. Performance evaluation

For RTES system of energy upgrade mode, the theoretical and experimental performance evaluation are defined as the following equations, in which the subscript ‘i’ and ‘r’ represent the theoretical and experimental condition, respectively.

For theoretical condition, the total heat input can be expressed:

$$Q_{in,i} = (\Delta H_L + Q_{s,L} + Q_{metal,L}) + (\Delta H_H + Q_{s,H} + Q_{metal,H}) \quad (4)$$

where the first term in the right side of the equation is the total heat consumption of the LTS reactor during the heat storage process including the desorption heat, sensible heat of LTS sorbent and the sensible heat of the metallic part of the LTS reactor; The second term is the total heat consumption of the HTS reactor during the heat upgrade process, including the desorption heat, sensible heat of the HTS sorbent and the sensible heat of the metallic part of the HTS reactor.

The heat release during energy release process can be expressed:

$$Q_{out,i} = \Delta H_H - Q_{s,H} - Q_{metal,H} \quad (5)$$

where the first term in the right side of the equation is the sorption heat of the HTS sorbent during energy release process; the second term is the sensible heat of the HTS sorbent; the last term is the sensible heat of the metallic part of the HTS reactor.

For experimental condition, the heat input of RTES system is similar to the theoretical condition, which can be expressed:

$$\begin{aligned} Q_{in,r} &= Q_{in, Hr} + Q_{in, Lr} \\ &= \int_0^{t_{in}} c_o \cdot m_o \cdot (T_{i,H} - T_{o,H}) dt + \int_0^{t_{up,L}} c_w \cdot m_w \cdot (T_{i,L} - T_{o,L}) dt \end{aligned} \quad (6)$$

where $Q_{in,r}$ is the real heat input provided by hot oil. t_{in} is the time for heat input of HTS reactor. m_o is the mass flow rate of oil. C_o is the specific heat of oil. $T_{i,H}$ and $T_{o,H}$ are inlet and outlet temperature of

HTS reactor. $t_{up,L}$ is the time for heat upgrade of LTS reactor. m_w is the mass flow rate of water. C_w is the specific heat of water. $T_{i,L}$ and $T_{o,L}$ are the inlet and outlet temperature of LTS reactor.

The heat release of RTES system can be expressed:

$$Q_{out,r} = \int_0^{t_{out}} c_o \cdot m_o \cdot (T_{o,H} - T_{in,H}) dt - \int_0^{t_{up,H}} c_o \cdot m_o \cdot (T_{in,H} - T_{o,H}) dt \quad (7)$$

where t_{out} is the time of heat release. $t_{up,H}$ is the time for heat upgrade of HTS reactor, which is different from $T_{up,L}$.

The heat exergy input of RTES system can be expressed:

$$E_{in} = \left(1 - \frac{T_0}{T_{in,H}}\right) \cdot Q_{in,H} + \left(1 - \frac{T_0}{T_{in,L}}\right) \cdot Q_{in,L} \quad (8)$$

where T_0 is the environmental temperature. $T_{in,H}$ is the average heat input temperature for HTS reactor. $T_{in,L}$ is the average heat input temperature for LTS reactor.

The heat exergy output of RTES system can be expressed:

$$E_{out} = \left(1 - \frac{T_0}{T_{out,H}}\right) \cdot Q_{out} \quad (9)$$

where $T_{out,H}$ is the average heat release temperature for HTS reactor.

Heat storage density HSD_m for mass density can be expressed:

$$HSD_m = \frac{Q_{out}}{M_{sorb}} \quad (10)$$

where M_{sorb} is the mass of HTS and LTS sorbent.

Heat storage efficiency COP_h can be expressed:

$$COP_h = \frac{Q_{out}}{Q_{in}} \quad (11)$$

Exergy efficiency can be expressed:

$$\eta_E = \frac{E_{out}}{E_{in}} \quad (12)$$

4. Results and discussions

4.1 Temperature trend

Since temperature of HTS and LTS reactor on different working conditions take the same trends, one representative working condition for RTES system is selected for illustration. Input heat temperature and heat release temperature are selected as 130°C and 140°C, respectively. Fig.3 show the temperature for the HTS and LTS reactor. Both inlet and outlet oil temperature of HTS reactor are

indicated in Fig.3a. Three processes, i.e. heat storage process, heat upgrade process and heat release process, are included, which take nearly 70 minutes in all. Heat storage process, heat upgrade process and heat release process take 30 minutes, 20 minutes and 40 minutes, respectively. Actually, it only take about 4-5minutes for HTS reactor to reach the heat release temperature, and it is extended for comparison between Fig.3a and Fig.3b. 20 minutes are consumed for the heat upgrade of LTS reactor since the water flowrate is not so large of water thermostat. As it shows in Fig.3a, in the heat storage process, temperature of HTS reactor first climbs remarkably, and the heat is mainly consumed by the sensible heat of the metallic part and composite sorbent. After 9-10 minutes, the temperature shows a slight decrease. This manifests that desorption of the HTS reactor happens. The inlet temperature is nearly 92°C, which is higher than the theoretical equilibrium temperature 80°C due to the heat transfer temperature difference. In the process desorption heat accounts for part of heating power, and sensible heat of metal and sorbent accounts for the other part. After the heat storage process, ammonia valve connecting HTS with LTS reactor is closed. The HTS reactor is heated again to heat release temperature. When the LTS reactor is heated to the set temperature as 80°C in Fig.3b, the ammonia valve is open again for heat release. In the heat release process, temperature first shows a peak then tend to be gentle. The maximum temperature increment is about 3.5°C, and average temperature increment is 2.7°C.

Fig.3b demonstrates both inlet and outlet temperature of the LTS reactor. It indicates that the LTS reactor is controlled as the environmental temperature in the heat storage process. Also in the 9-10 minute, the outlet temperature of the LTS reactor shows a little increase due to the sorption heat of the LTS reactor. After that the ammonia valve is closed, the LTS reactor is heated to 80°C as set temperature. Then the valve is open again, the heat release process happens. It can be noted that a remarkable decline of the temperature of LTS occurs. This is mainly because the obvious desorption heat takes effect in the heat release process.

Table 1 shows the largest outlet temperature increment i.e. the largest difference between inlet and outlet temperature of HTS reactor for RTES system under the condition of different heat release temperature. It is clear that in the heat release process the largest outlet temperature increment of HTS reactor decreases with the increase of heat input temperature. Also worth noting that the largest outlet

244 temperature increment of HTS reactor range from 2.5°C to 4°C and from 2.3°C to 3.7°C when the heat
 245 inlet temperature of LTS reactor are 70°C and 80°C, respectively.

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250 **Fig. 3.** Temperature in heat storage, heat upgrade and heat release process (a) inlet and outlet
 251 temperature of HTS reactor; (b) inlet and outlet temperature of LTS reactor.

252

253 **Table 1.** The largest outlet temperature increment of HTS reactor for RTES system.

Heat input temperature (°C)	Heat release temperature (°C) (LTS reactor 70 °C)	The largest temperature increment (°C)	Heat release temperature (°C) (LTS reactor 80 °C)	The largest temperature increment (°C)
125	130	4.0	135	3.7
130	135	3.8	140	3.5
135	140	3.2	145	2.9
140	145	2.8	150	2.6
145	150	2.5	155	2.3

4.2 Heat storage density of RTES system

Heat storage density of RTES system is analyzed based on the mass of both HTS and LTS composite sorbent as shown in Fig.4. Fig.4a and Fig.4b show heat storage density of RTES system when temperature of the LTS reactor are 70°C and 80°C in the heat release process. The highest heat storage density is about 662 kJ/kg and 596 kJ/kg when the heat input temperature is 125°C and heat release temperature are 130°C and 135°C, respectively. For different heat release temperature, heat storage density decreases with the increment of heat release temperature. This is mainly because the higher heat release temperature is, the more heat will be consumed for the HTS reactor when it is heated to the heat release temperature. Also the higher heat release temperature will result in the increase of heat loss for the HTS reactor. For different working conditions, the heat storage density range from 359 kJ/kg to 662 kJ/kg.

(a)

(b)

Fig. 4. Heat storage density for RTES system when temperature of the LTS reactor (a) 70°C; (b) 80°C.

Fig.5 shows the heat storage efficiency and exergy efficiency for different heat input temperature from 125°C to 145°C in term of 70°C and 80°C LTS reactor temperature. Both heat storage efficiency and exergy efficiency are determined by the quantity and exergy of heat input and heat release. The increase of heat input temperature will decrease the heat storage efficiency and exergy efficiency. The heat storage efficiency and exergy efficiency of 70°C LTS reactor temperature is higher than that of 80°C LTS reactor temperature. The highest energy efficiency and exergy efficiency are 40.6% and 47%, respectively when the heat input temperature is 125°C. For different heat input and release temperature, the energy efficiency and exergy efficiency range from 27.5% to 40.6% and from 32.5% to 47%, respectively.

(a)

(b)

Fig. 5. The heat storage efficiency and exergy efficiency vs. heat input temperature (a) heat storage efficiency; (b) exergy efficiency.

Fig.6 shows the heat storage efficiency with different mass ratios between the metal and sorbent when heat release temperature is 150°C. It indicates that heat storage efficiency will increase with the decrease of ratio between metal to sorbent. Also worth noting that when the mass ratio between metal and sorbent mass decreases to 3:1, the highest heat storage efficiency can reach 0.548, which is closer to the theoretical value of 0.67. Compared with the experimental result, the maximum improvement is able to reach 62.5% for heat storage efficiency, which demonstrates good potential performance of RTES system. According to the reference[21], the mass ratio between metal and sorbent could be decreased into 3:1 by the compressed technology rather than filling the sorbent into the fin gap of fin

tube. This also provides the possibility for further improving the performance of energy storage and upgrade.

Fig. 6. The heat storage efficiency under the condition of 150°C release temperature.

5. Comprehensive comparison among three working modes of RTES system

In order to comprehensively investigate the RTES system, three different modes, namely heat upgrade, direct heat supply and combined heat and cooling, are compared in term of energy density, energy efficiency and exergy efficiency based on our previous work[23, 24]. Since both the heat and cold output may concern for different working modes, descriptions of energy density, energy efficiency and exergy efficiency are used in Fig.7, Fig.8 and Fig.9, which are different from the descriptions above. The heat input temperature is selected from 130°C to 145°C for three different modes. For the heat upgrade mode, the heat release temperature is selected from 140°C to 155°C. For direct heat supply mode, the heat release temperature is 70°C. For combined heating and cooling mode, the heat and cold release temperature are selected as 35°C and 15°C, respectively.

As Fig.7 shows, the energy density for the modes of direct heat supply and combined heat and cooling take the same trends while the upgrade mode shows the reverse trend. This is mainly because the heat release temperature lies in the reverse position when compared with heat input temperature.

When the heat input temperature reach 135°C, energy density for direct heat supply are closest to that for heat upgrade, which shows a 6% increment. With heat input temperature increasing, the gaps among three different modes become larger. The highest energy density for combined heat and cooling mode is able to reach 1710 kJ/kg, which is 74% higher than that of the direct heat supply and 3.76 times higher than that of heat upgrade when the input temperature is 145°C.

Fig. 7. Energy density of RTES system for different working modes.

As for energy and exergy efficiency shown in Fig.8 and Fig.9, three working modes indicate the same trends as that of energy density. One worthy noting fact is that the gaps of exergy efficiency among the three different working modes are much smaller than that of the energy efficiency and energy density. The smallest gaps of exergy efficiency between heat upgrade and direct heat supply as well as between direct heat supply and combined heat and cooling are as low as 7.3% and 12.5% when heat input temperature is 130°C. Comparably, the smallest gap of energy efficiency between heat upgrade and direct heat supply as well as between direct heat supply and combined heat and cooling could reach 20.5% and 73.1%, respectively. The reason lies in that although the quantity of heat release for heat upgrade is much lower than that of direct heat supply and combined heat and cooling, the quality of heat release could be improved by the upgrade mode. It shows the advantages for the waste

heat recovery in large-scale industrial processes, and the upgrade heat is able to be utilized for the industrial process again. In contrast, the direct heat supply and combined heat and cooling modes mainly supply the heat and cold to the end user.

Fig. 8. Energy efficiency of RTES system for different working modes.

Fig. 9. Exergy efficiency of RTES system for different working modes.

6. Conclusions

An innovative $\text{MnCl}_2\text{-CaCl}_2\text{-NH}_3$ RTES system for energy storage and upgrade is established. Resorption energy storage process is investigated with different heat input and heat release temperature. Besides, three different working modes, i.e. direct heat supply, heat upgrade and combined heat and cooling supply are comprehensively analyzed and compared. Conclusions are

yielded as follows:

(1) For heat upgrade mode, the largest outlet temperature increment i.e. the largest difference between inlet and outlet temperature of HTS reactor decreases with the increase of heat input temperature. Also worth noting that the largest outlet temperature increment of HTS reactor range from 2.5°C to 4°C and from 2.3°C to 3.7°C when the heat inlet temperature of LTS reactor are 70°C and 80°C, respectively.

(2) The highest heat storage density is about 662 kJ/kg and 596 kJ/kg when the heat input temperature is 125°C and heat release are 130°C and 135°C, respectively. For different heat release temperature, heat storage density decreases with the increment of heat release temperature. For different working conditions, the mass heat density range from 359 kJ/kg to 662 kJ/kg.

(3) The highest energy efficiency and exergy efficiency are 40.6% and 47% when the heat input temperature increases from 125°C to 145°C. For different heat input and release temperature, the energy efficiency and exergy efficiency range from 27.5% to 40.6% and from 32.5% to 47%, respectively.

(4) For different working modes, when the heat input temperature reach 135°C, energy density for direct heat supply are closest to that for heat upgrade, which shows a 6% increment. The highest energy density for combined heat and cooling mode is able to reach 1710 kJ/kg, which improves 74% higher than that for the direct heat supply and 3.76 times higher than that for the heat upgrade. The gaps of exergy efficiency among the three different modes are much smaller than that of the energy efficiency. The smallest gaps of exergy efficiency between heat upgrade and direct heat supply as well as between direct heat supply and combined heat and cooling are

as low as 7.3% and 12.5% when heat input temperature is 130°C. Comparably, the corresponding smallest gap of energy efficiency are 20.5% and 73.1%, respectively.

RTES system for energy upgrade mode can overcome the drawbacks of STES. Low grade thermal energy is stored in form of chemical bonds in the sorption process, and the energy upgrade can be accomplished by using the same resorption system. Although the energy efficiency is reduced to some extent, the heat release enjoy larger application fields for further utilization, which is the largest advantage of resorption energy upgrade.

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