



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



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ARTICLE INFO

Article history:

Received 3 January 2017

Received in revised form 4 February 2017

Accepted 6 February 2017

Available online 24 February 2017

Keywords:

Resorption

Composite sorbent

Energy upgrade

Energy storage density

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.

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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

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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)

Greek letters

ΔH	enthalpy of sorbent
Δx	sorption quantity variation (kg/kg)

ρ	density of ammonia (kg/m ³)
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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

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 $MnCl_2$ - $CaCl_2$ - 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 $MnCl_2$ - $CaCl_2$ - 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 $MnCl_2$ - $CaCl_2$ - 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 $MnCl_2$ - $CaCl_2$ - 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 Eq. (1).

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

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].

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