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Experimental investigation of energy and exergy performance of short term adsorption heat storage for residential application

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ABSTRACT

Energy and exergy performance of adsorption storage system was studied experimentally for residential application. A fin-coated heat exchanger was adopted for a sorption bed to quicken the charging process. When the regeneration temperature was 70 °C, ambient temperature was 30 °C, HTF (heat transfer fluid) inlet temperature for the adsorption bed was 30 °C, results showed that the heat ESD (energy storage density) was approximately 805 kJ/kg with the energy efficiency approximately 96%. The exergy efficiency was 26.7% and the loading difference was 0.164. In this study the mass flow rate of the adsorption bed affected more on the storage performance than that of the desorption bed. As the mass flow rate was increased, the ESD increased while the exergy efficiency decreased due to the larger exergy destruction caused by pressure drop. Increasing regeneration temperature and decreasing adsorption temperature could make the ESD and energy efficiency increased, but the exergy efficiency decreased. As ambient temperature was increased, total ESD and energy efficiency increased, and overall exergy efficiency decreased. A larger loading difference could be achieved with increasing the adsorption bed HTF mass flow rate, regeneration temperature, and inlet temperature of HTF for the evaporator, or decreasing inlet temperature of HTF for the adsorption bed.

1. Introduction

TES (thermal energy storage) system is a crucial energy system, which can reduce or eliminate the cause of peak electric power loads in buildings, and utilize benefits of the waste heat recovery and renewable energy [1,2]. Among several typical storage systems, the sensible TES technology is a mature technology and has already been implemented in many large-scale demonstration projects and plants. However, ESD (energy storage density) of the sensible TES is relatively low, leading to large storage volume. In contrast, the latent TES technology has a much higher ESD with a narrow temperature interval. However, the latent materials usually have the issues of crystallization, corrosion, etc. In addition, they can only storage energy efficiently around phase transition temperature level.

Regarding sorption TES technologies, adsorption is the general phenomenon resulting from the interaction between a solid (adsorbent) and a gas (refrigerant), based on a reversible physical or chemical reaction process. In theory, it has a high ESD for adsorption materials. Moreover, input and output temperature levels of the adsorption TES can be determined by practical demand and operating conditions, exhibiting some extent of flexibility. In addition, the adsorption heat can be stored with a long time with no pollution and negligible heat loss for long term use.

Recently there are raising research activities on adsorption chillers and heat pumps from both material and prototype aspects. Janchen et al. [3] investigated the AlPO4 molecular sieves as well as SAPO-34 as compared with zeolites similar values of adsorbed amounts of water and the energy densities. However, the average temperatures for the desorption of the water decreases at either higher than as well from >450 K or lower than to <400 K, which classifies the silicoaluminophosphate between the common zeolites and the salt hydrates with regard to the properties as thermochemical storage material. Aristov [4] gave a comprehensive review about different kinds of materials on a huge choice of novel porous solids which may be used for adsorption transformation of low temperature heat, and it is beneficial for further consolidating international activities in materials science and heat adsorption applications. Another review article by Yu et al. [5] analyzed the sorption working pairs in detail and showed the technical challenges and perspectives for sorption thermal storage technologies. San and Hsu [6] studied a multi-bed adsorption heat pump using SWS-1L composite adsorbent and water as the working pair. Under the desorption temperature of 120 °C, with SWS-1L composite adsorbent to substitute a regular-density silica gel in the adsorbers,

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Nomenclature

Abbreviations

C_p	specific heat capacity [kJ/kg·K]
DAQ	data acquisition
ESD	energy storage density
Ex	accumulated exergy [kJ]
$\dot{Ex}$	instant exergy flow rate [kW]
h	enthalpy [kJ/kg]
HTC	heat transfer coefficient
HTF	heat transfer fluid
HX	heat exchanger
OD	outer diameter [mm]
P	pressure [kPa or bar]
Q	accumulated energy [kJ]
$\dot{Q}$	heat transfer rate [kW]
s	entropy [kJ/kg·K]
$\dot{Q}$	heat transfer rate [kW]
T	temperature [°C]
TES	thermal energy storage
Z01	Mitsubishi Plastics AQSOA FAM-Z01

Greek symbols

ψ	specific exergy [kJ/kg]
ρ	density [kg/m^3]
Δ	change or difference
ε	exergy efficiency
η	energy efficiency

Subscripts

ads	adsorption
charg	charging
cond	condenser
delivered	energy or exergy delivered into the system
des	desorption
disch	discharging
evap	evaporator
in	inlet to a component
out	out of a system or the fluid outlet of a component
recovered	energy or exergy recovered from the system

the coefficient of performance and specific cooling power values can be increased by 51% and 38.4%, respectively. Freni et al. [7] investigated the novel composite water sorbent "silica modified by calcium nitrate" (SWS-8L) for utilization in adsorption chillers driven by low-temperature heat around 90~95 °C. Experimental cooling, mass specific cooling power and volumetric specific cooling power obtained were 0.18~0.31 (cycle time 10 minutes), 190~389 W/kg dry sorbent and 104~212 W/d m^3, respectively. Dawoud et al. [8] studied the zeolite-water adsorption heat pump with 13.2 kg of zeolite 13X under desorption temperature 150 °C. Storage capacities of 2.7 and 3.1 kWh had been measured at the evaporator inlet temperatures of 10 and 40 °C, respectively, corresponding to thermal energy storage densities of 80 and 92 kWh/m^3 based on the volume of the adsorber unit. Wu et al. [9] systematically studied a family of composite sorbents was prepared by impregnating silica gel in the solution of the hygroscopic salt $CaCl_2$ for solar heat storage. The characteristics of water adsorbed on the composite sorbents prepared under different impregnating conditions were measured by a micromeritics gas adsorption analyzer, a Calvet-type microcalorimeter and an open-type gravimetric method. Results showed that the composite sorbent prepared by impregnating in the $CaCl_2$ solution of 30% showed a high and stable storage capacity of 1020 kJ/kg with desorption temperature of approximately 90 °C. This study demonstrates a great potential in controlling the sorption characteristics as well as the storage properties of the composite sorbents by optimizing the impregnating variables to meet the specific demands of solar heat storage.

Currently, regarding the adsorption TES, there is limited research work from the prototype-scale or system-scale for low-grade heat source below 80 °C. A closed adsorption cold storage system with a water/zeolite 13X as working pair was investigated by Lu et al. [10] for the locomotive air conditioning application. Results showed that the experimental cold storage capacity was 5.5 kWh with 140 kg of 13X zeolite grains (i.e. ESD was approximately 141 kJ/kg). However, the heat source was exhaust gas from a locomotive, whose temperature is as high as 350 °C. Institut für Solartechnik SPF from Switzerland also studied water/zeolite 13X for the closed adsorption TES with heat source temperature of 180 °C [11]. Another working pair H_2O/silica gel for closed adsorption storage was investigated within the framework of the EU-project MODESTORE [11], and the silica gel used in this prototype was microporous silica gel Grace 127B. The storage capacity was 13 kWh with heat source temperature near 90 °C. In addition, in order to utilize heat source with a low temperature, one study by Li et al. [12] proposed a dual-mode sorption energy storage system with thermodynamic analysis, and the heat input temperature can be decreased from original 99 °C to 81 °C by employing the two-stage regeneration method. As discussed, there is very limited research work for the prototype-scale or system-scale with low-grade heat source below 80 °C, and also there are less extensive studies for the adsorption TES under different operating conditions.

Regarding assessment of TES units, currently energy analysis based on first law of thermodynamics is still the commonly used method. However, it does not evaluate how close the system performance approaches to the ideal storage performance. Exergy analysis based on the second law of thermodynamics can overcome shortcomings of energy analysis. Exergy analysis would be the major part for TES performance assessment. Reasonable energy and exergy analysis for storage system performance evaluation can achieve an optimized system for the application of interest. Previous studies focused on the investigation on the latent heat storage and less on the adsorption heat storage of TES energy and exergy performance, especially for the exergy performance. One latent storage unit was investigated for the entropy generation number by El-Dessouky and Al-Juwayhel [13] under various working temperatures and HTF (heat transfer fluid) mass flow rates. A recent study by Ezan et al. [14] investigated energy and exergy efficiencies for a shell-and-tube type latent heat TES system for charging and discharging process. One review article by Jegadheeswaran et al. [15] showed the extensive summaries for the latent storage exergy performance. There are few works for exergy performance investigation. Regarding the sorption TES system, recently, Abedin and Rosen [16] performed the exergy analysis and showed that the sorption TES system may be as efficient as, and more compact than other types of the TES system. Currently there are few studies from the prototype-scale or system-scale to investigate the adsorption TES energy and exergy performance.