Effects of storage period on the performance of salt composite sorption thermal energy storage

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Abstract

Effects of storage duration, high-conductivity additives and non-condensable gases on the storage performance of salt composite sorption thermal energy storage are experimentally investigated. We observed that sorption hot storage is more suitable for short-term storage, since there is a 58% decrease in energy storage density (ESD) from 1.03 (no storage-time) to 0.43 MJ·kg^{-1} (seasonal applications). The hot storage ESD is almost the same for silica gel-$CaCl_2$ and silica gel-$CaCl_2$-graphite flake (1.04 MJ·kg^{-1}), while the averaged specific discharge power of the composite with graphite flake is higher. A 25% decrease in the ESD of seasonal cold storage is observed, compared to the cyclic operation, when 1.7 kPa pressure build-up in condenser occurred. This indicates the importance of occasional degassing for long-term applications. For desorption temperature of 90 °C, proper heat insulation can increase the specific power up to 60 W·kg^{-1}.

Keywords: sorption thermal energy storage, residual gas, storage period, salt composites, heat loss

Introduction/Background

Thermal energy storage (TES) is essential for efficient use of intermittent renewables. Among TES systems, sorption thermal energy storage (sorp-TES) shows great potential for short- and long-term storage, because of high energy storage density (ESD) and negligible heat loss [1]. However, Schreiber et al. [2] showed that long-term storage dramatically decreased the ESD of a high-temperature (i.e. 250 °C) Zeolite-based hot storage sorp-TES. Composite sorbents, salts in porous matrix, provide the highest ESD [3], although salt composites are corrosive to most heat exchanger materials and corrosion reactions release non-condensable gasses, causing pressure build-up in the sorber bed and evaporator/condenser. Glaznev et al. [4] showed that presence of even small amount of residual gas can dramatically decrease the adsorption rate and the cooling power.

In this study, the effect of storage duration, from no storage to few minute-storage and seasonal application, is examined using a custom-built low-temperature driven sorp-TES with silica gel-$CaCl_2$ and silica gel-$CaCl_2$-graphite flake. Similar to the study which is performed by Osterman et al. [5] for a paraffin latent thermal energy storage, steady-state heat loss of the sorber bed is assessed. Moreover, effects of residual gas build-up inside the sorber bed on ESD, for both cold and hot storage, are investigated. Moreover, the effects of adding high-conductive additives, graphite flake, to the salt composite on the ESD and discharge power are studied.

Experimental study

Our custom-made closed sorption prototype is shown in Figure 1 and consists of: i) two sorber beds, fin-tube heat exchanger; ii) a condenser, shell-and-tube heat exchanger; and iii) an evaporator, custom-built capillary-assisted low-pressure evaporator. One of the sorber beds was filled with 1.302 kg silica gel-$CaCl_2$ (SG-CC: 55 wt% B150 silica gel, 30 wt% $CaCl_2$ and 15 wt% PVA), while the second one was filled with 1.513 kg silica gel-$CaCl_2$-graphite flake (SG-CC-G: 42 wt% B150 silica gel, 23 wt% $CaCl_2$, 20 wt% graphite flakes and 15 wt% PVA). Table 1 lists specifications of the sorbent composites with and without graphite flakes. Each bed was examined separately. Prior to the experiments, the entire sorption system was evacuated at 90 °C for several hours to remove the residual gas. During the charging process, each sorber bed was heated by an external water loop and the desorbed water vapour was transferred to the condenser through a one-way valve. Any non-condensable gas in the sorber bed also flowed to the condenser. During the storage process, the sorber bed was isolated from the evaporator and condenser. To study the effect of storage duration on the performance, the sorp-TES was discharged in a cyclic mode (no storage time), and afterwards, for various storage durations. In cyclic operation (considered as a baseline test), periodically a quick degassing (few seconds) was performed between the half-cycles, to maintain a constant condenser pressure. For other storage durations, the degassing was not performed, to study the effect of the presence of residual (non-condensable) gases on the storage performance. For seasonal application, the system was turned off and reached the ambient temperature, which took 1 day for this testbed. In the discharging process, the valve between the evaporator and the sorber bed was opened and water vapour went to the sorber bed, at a lower pressure than that of the evaporator. For cold storage, the cooling energy provided by evaporator and for hot storage the heat (adsorption and sensible) produced in sorber bed were used.

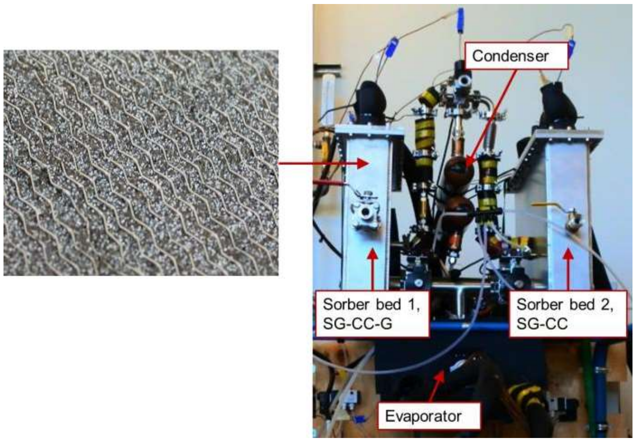


Figure 1. Sorption thermal energy storage prototype, including: i) 2 sorber beds, ii) condenser, and iii) evaporator.

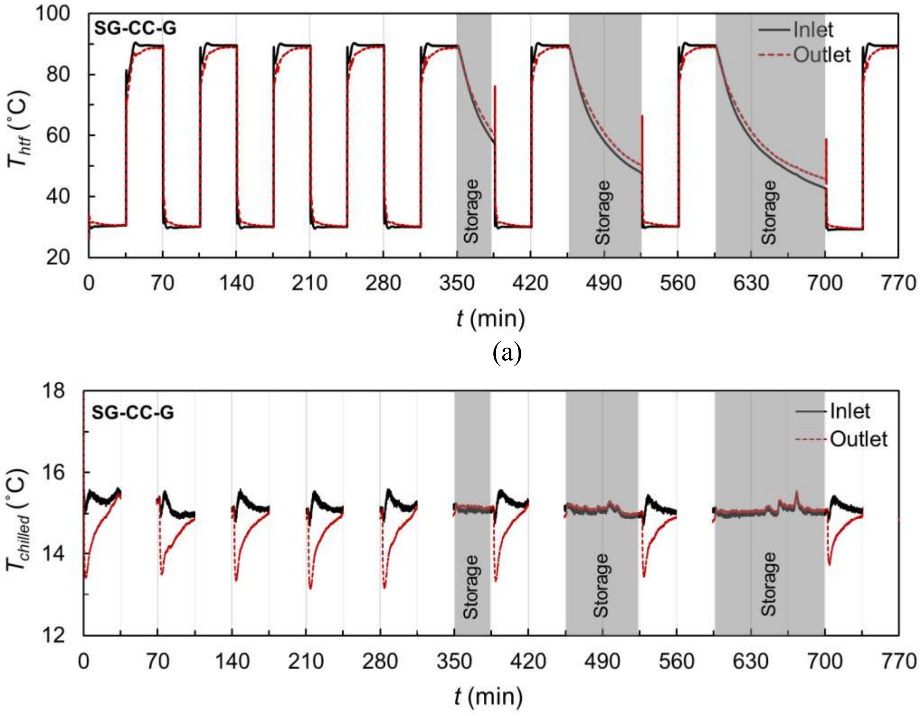
Table 1. Specification of the sorbent composite of the sorption samples: Silica gel + $CaCl_2$ + graphite flakes (20%) and Silica gel + $CaCl_2$.

	Silica gel + $CaCl_2$ + graphite flakes (20%)	**Silica gel + $CaCl_2$**
Composition	42% B150 silica gel 23% $CaCl_2$ 15% PVA 20% graphite flakes	55% B150 silica gel 30% $CaCl_2$ 15% PVA
m_{ads} (kg)	1.513	1.302
k_{ads} ($W \cdot m^{-1} \cdot K^{-1}$)	0.231 +/- 0.006	0.098 +/- 0.002
$c_{p,ads}$ ($MJ \cdot m^{-3} \cdot K^{-1}$)	0.45 +/- 0.03	0.42 +/- 0.06

Discussion and Results

Inlet and outlet temperatures of the sorber bed heat transfer fluid and inlet and outlet temperatures of the evaporator chilled water are shown in Figure a and Figure b. As depicted in Figure 2, after five cyclic charging-discharging, storage times of 35, 70 and 105 min are considered. Figure 3a shows the ESD and specific discharge power of the SG-CC and SG-CC-G sorber beds, for cold and hot storages. As shown in Figure 3a, ESD of cold storage of SG-CC bed is higher than SGCC-G bed (0.57 compared to 0.39 $MJ \cdot kg^{-1}$), due to the more active sorbent and more evaporation in the evaporator. ESD of hot storage for SG-CC-G (thermal conductivity of 0.231± 0.006 W·m^{-1}·K^{-1}) and SG-CC (thermal conductivity of 0.098±0.002 W·m^{-1}·K^{-1}) are almost the same (1.04 MJ·kg^{-1}). Similar to the cold storage ESD, the specific discharge power for cold storage is also higher for the SG-CC bed compared to SG-CC-G one. The discharge power for the first 10 min of discharge process for the hot storage is higher for the bed with graphite flake (1.30 kW·kg^{-1}) compared to the bed without graphite flake (1.25 kW·kg^{-1}), because of the higher thermal diffusivity of graphite flake, which expedites the discharging process and makes it more suitable for fast-heat delivery applications. However, the overall specific discharge power, similar to the ESD, is slightly higher for the SG-CC bed (487 W·kg^{-1}) compared to the SG-CC-G bed (476 W·kg^{-1}).

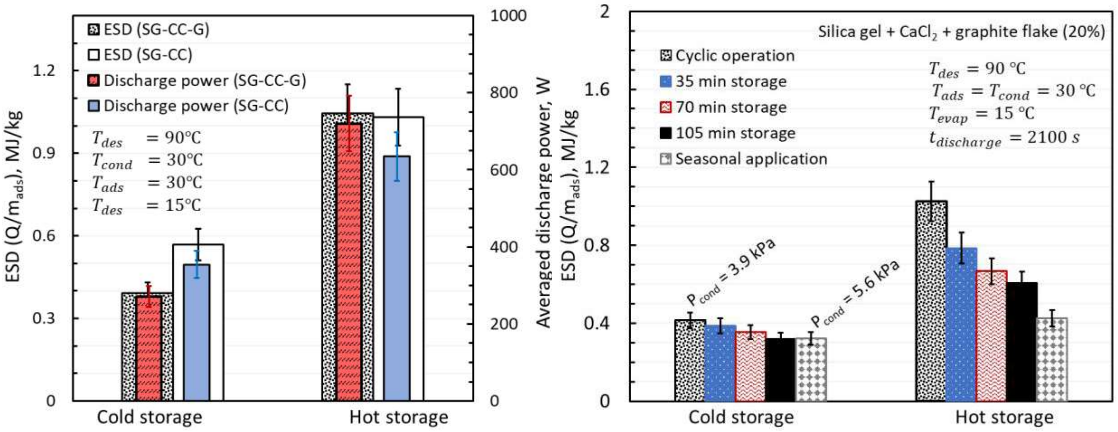
Figure 3b shows the effect of storage duration on the cold and hot storage ESD. Cold ESD slightly decreases from the cyclic mode to a few minutes of storage and seasonal application. Sorp-TES systems are known for having no cold energy loss [6] and this drop in the cold ESD is due to the pressure build-up inside the condenser, as a result of existence of non-condensable gases by the corrosion reactions in the salt composite sorber bed. The residual gases add to the mass transfer resistance inside the sorber bed and, other than using corrosion-resistant materials and corrosion-protection layer, as stated in ref. [7], occasional degassing is necessary for long-term use of a closed sorption system, due to the residual gases and leakage. As shown in Figure 3b, the pressure difference between the sorber bed and the condenser is decreased during the time, falling by 38 Pa from the cyclic mode to seasonal mode, which causes a 25% decrease in the cold ESD. A significant decrease is observed in the hot ESD from the cyclic operation mode (1.03 MJ·kg^{-1}) to seasonal application (0.43 MJ·kg^{-1}), due to the (non-condensable gases) pressure increase in the condenser and sensible heat loss in the sorber bed. The latter highlighted that, for hot storage, the sorp-TES systems are suitable for short-term storage rather than seasonal applications, where a part of the input sensible heat can be discharged as well.



(a)

(b)

Figure 2. (a) Temperature of heat transfer fluid of the sorber bed with Silica gel + CaCl$_2$ + graphite flake versus time and (b) temperature of evaporator chilled water versus time.



(a) (b)

Figure 3. (a) Effect of high-conductive additives on ESD and discharge power and (b) effects of storage duration and residual gas on ESD.

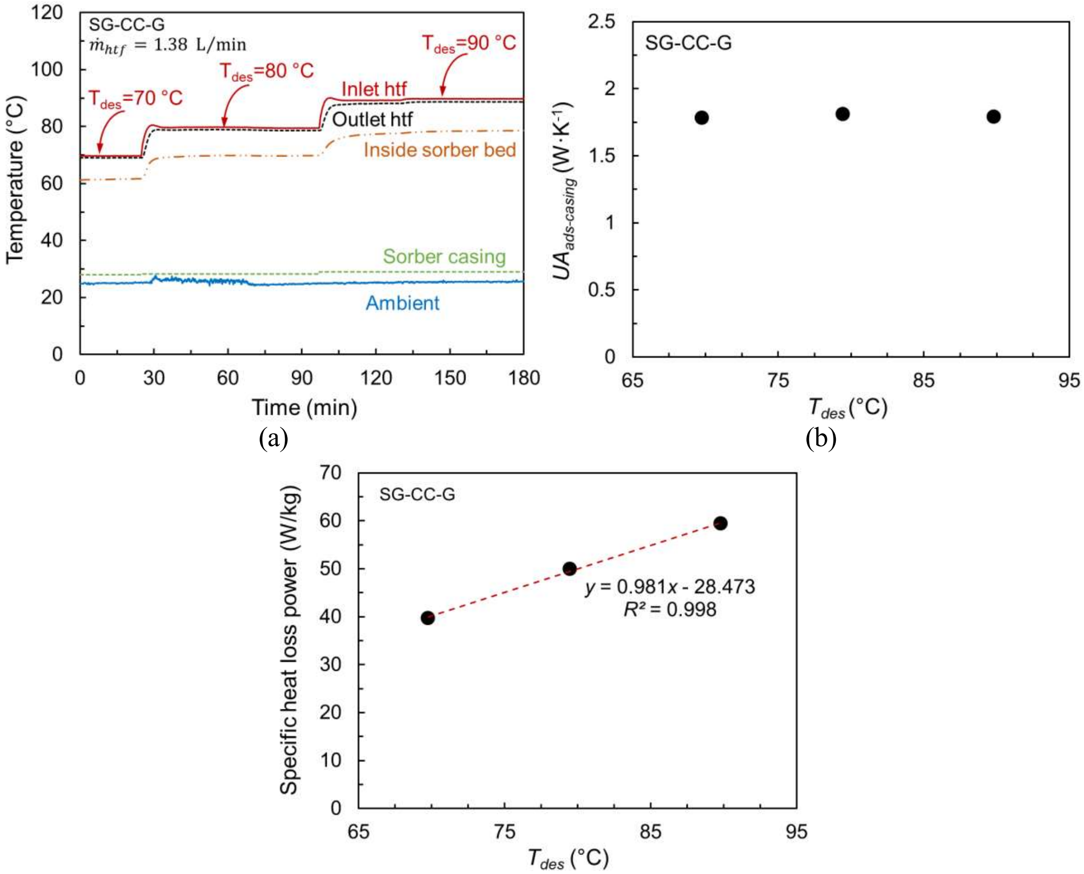
Moreover, the steady-state heat loss during the charging process is studied here. After the sorber bed is fully desorbed, it is isolated from the evaporator/condenser and vacuumed by a vacuum pump. Afterwards, the sorber bed is heated up in three steps to the desorption temperatures of 70, 80 and 90 °C. As shown in Figure 4a, for each step, the heating at constant heat source temperature is continued to achieve a steady-state condition (i.e. ΔT_{htf} is constant). Under steady-state condition, thermal losses can be determined from the steady-state constant temperature difference of the heat transfer fluid, using the following equation:

$$\frac{\mathrm{dQ}}{\mathrm{dt}} = \dot{\mathrm{m}}_{\mathrm{htf}} \mathrm{c}_{\mathrm{p,htf}} \left(\mathrm{T}_{\mathrm{out,htf}} - \mathrm{T}_{\mathrm{in,htf}}\right) + (\mathrm{UA})_{\mathrm{loss}} \left(\mathrm{T}_{\mathrm{casing}} - \mathrm{T}_{\mathrm{sorbent}}\right) = 0 \qquad (1)$$

where Q, $\dot{\mathrm{m}}_{\mathrm{htf}}$, $\mathrm{c}_{\mathrm{p,htf}}$, $\mathrm{T}_{\mathrm{in,htf}}$, $\mathrm{T}_{\mathrm{out,htf}}$, $(\mathrm{UA})_{\mathrm{loss}}$, $\mathrm{T}_{\mathrm{casing}}$ and $\mathrm{T}_{\mathrm{sorbent}}$ are the total heat transfer rate, mass flowrate, specific heat capacity, inlet and outlet temperatures of the heat transfer fluid, overall heat transfer coefficient of heat loss, outside temperature of casing and the sorbent temperature inside the sorber bed, respectively. Figure 4b shows the heat transfer coefficient of thermal loss between the sorber bed and the casing outside temperature. The averaged $\mathrm{UA}_{\mathrm{loss}}$ is 1.79 $\mathrm{W \cdot K^{-1}}$, which can, in part, as a result of not insulating the sorber casing. As shown in Figure 4c, the specific heat loss power shows a linear trend versus the desorption temperature. At desorption temperature of 90 °C, using proper thermal insulation, can add up to 60 $\mathrm{W \cdot kg^{-1}}$ to the specific power of the storage system. The obtained heat loss as a function of desorption temperature, should be fed to the sorp-TES models for more accurate of the storage system.

Conclusions

An experimental study was conducted to investigate the effects of storage time, noncondensable gases, high-conductivity additives and steady-state heat loss on the overall performance of a salt composite sorption thermal energy storage system (sorp-TES). For hot storage, the sorp-TES was preferable for short-term storage, due to a 58% decrease in ESD, from 1.03 (no storage-time) to 0.43 $\mathrm{MJ \cdot kg^{-1}}$ (seasonal applications). There was no significant difference between the hot storage ESD of the silica gel-$\mathrm{CaCl_2}$ and silica gel-$\mathrm{CaCl_2}$-graphite flakes. However, the averaged specific discharge power of the graphite flake composite, for the first 10 min of discharge process, was higher (1.30 $\mathrm{kW \cdot kg^{-1}}$ compared to 1.25 $\mathrm{kW \cdot kg^{-1}}$). The measured ESD of seasonal cold storage was 25% less than that of the cyclic operation when a 1.7 kPa pressure built-up in the condenser due to the corrosion reactions with the heat exchangers, which indicated the importance of using of corrosion-protective layers as well as occasional degassing for long-term applications. Study of steady-state heat loss between the inside of the sorber bed and the outside of the casing in the charging process showed that the averaged heat loss coefficient was 1.79 W·K^{-1}. Specific power, at desorption temperature of 90 °C, could be increased up to 60 W·kg^{-1} with using proper thermal insulation.



(a) (b)

(c)

Figure 4. (a) Temperature versus time for inlet and outlet of heat transfer fluid, inside the sorber bed, sorber casing and ambient, (b) heat loss coefficient $UA_{ads\text{-}casing}$ from the adsorber bed to the outside of the sorber bed casing versus desorption temperature and (c) specific heat loss power versus desorption temperature.

Acknowledgements

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