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Experimental testing of a single-bed adsorption unit for thermal energy storage applications

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Abstract

In this article, a single-bed silica gel/water adsorption test bench is tested as sorption thermal energy storage (STES) system operating with intermittent ad/desorption phases. Experimental tests were addressed to evaluate the heat storage performance in terms of heat storage energy density and charging/discharging power, considering $T_{ads,in}$ = 30 °C (discharging phase) and 90 °C (charging phase), flowrates 0.4 m^3/h (all components), and $T_{cond,in}$ = 30 °C (charging phase). Specific focus is placed on studying the impact of the vapour flow variation between the evaporator and condenser and the adsorber bed, as a parameter that could influence the overall ad/desorption processes. Obtained data shows that through the vapour flow reduction during the discharging phase, almost constant temperature and heat transfer rate are obtained at the adsorption bed. This corresponds to a reduction of 52% of the peak power of the adsorber reactor and an increase of 46% in the phase's duration. Energy density per m^3 of silica gel for the adsorber reactor was 152 kWh/m^3. The flow control valve had less impact on the charging phase, leading to a reduction of 6-12% in the condenser's and adsorber's peak power. The corresponding energy density of the condenser per m^3 of silica gel was 170 kWh/m^3.

Keywords: adsorption, energy storage, silica gel/water, thermochemical.

Introduction/Background

Thermochemical Energy Storage (TES) systems offer high flexibility, enabling peak shaving, load shifting, energy efficiency improvements, and greater use of renewable sources, thereby reducing greenhouse gas emissions, particularly in heating and cooling sectors. Among TES technologies, Sorption Thermal Energy Storage (STES) showed high potential of obtaining high heat storage performance, as reported in literature [1-4]. In this work, a single-bed adsorption system employing the silica gel/water working pair is tested to explore its potential as a STES system, particularly investigating the influence of the regulation of the water vapour flow between the evaporator/condenser and the adsorber on the overall process. Firstly, description of the adsorption test-bench located at Politecnico di Milano is provided and the testing procedure is detailed. Afterward, testing results are reported for a base-case operating under typical heat storage conditions and the achieved performance are discussed.

Discussion and Results

The scheme of the experimental setup used for testing STES unit is presented in Figure 1a. The core system of the single-bed test bench is composed of the adsorption reactor, a falling-film evaporator, and a condenser, as shown in Figure 1b. Three hydraulic circuits are used as heat sinks/sources for the adsorption/desorption stages (see Figure 1a): the hot-temperature (HT) circuit is composed of a 200 L tank with a 9-kW resistance, the low-temperature circuit (LT) sets the inlet chilled water temperature with a 500 L tank and a 4.6-kW chiller, and the medium-temperature (MT) circuit is composed of two large (> 3000 L) tanks at controlled temperature which water is mixed to obtain the desired setpoint. Being a single-bed adsorption system, the working modalities are split into an adsorption/evaporation (discharge) phase, and a desorption/condensation (charge) stage, separated by the respective cooling and heating intermediate phases. After cooling the adsorption bed, the discharging phase is started by opening the valve connecting it with the evaporator. Once the adsorption/evaporation phase is completed, the heating stage begins, sending hot water from the HT circuit to the adsorption reactor, while water from the MT circuit is redirected to the condenser. When the bed's pressure is higher than the pressure of the condenser, the valve connecting these two components is opened, and the desorbed vapor begins to flow to the condenser (charging phase). Main variables to be analysed are calculated in equations (1) to (6).

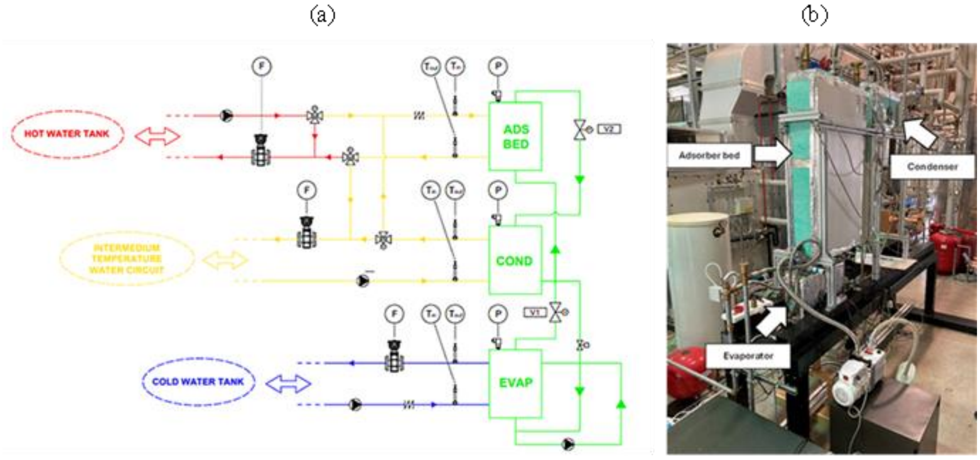

Figure 1. Adsorption test bench: (a) hydraulic circuits (b) single-bed laboratory unit

$$Q_{ADS} = \dot{m}_{ADS} \cdot cp_{ADS} \cdot (T_{ads,out} - T_{ads,in}) \quad (1)$$

$$Q_{cond} = \dot{m}_{cond} \cdot cp_{cond} \cdot (T_{cond,out} - T_{cond,in}) \quad (2)$$

$$EE_{ADS} = \int_{t_i}^{t_f} Q_{ADS} \cdot dt \quad (3)$$

$$EE_{cond} = \int_{t_i}^{t_f} Q_{cond} \cdot dt \quad (4)$$

$$\dot{EE}_{ADS} = \frac{EE_{ADS} \cdot \rho}{M_{ADS}} \quad (5)$$

$$\dot{EE}_{cond} = \frac{EE_{cond} \cdot \rho}{M_{ADS}} \quad (6)$$

Knowing the specific heat (cp),, flowrates ($\dot{m}$) and temperatures (T) of the working fluids flowing through each component, heat transfer rates for the adsorbent reactor (Q_{ADS}) and condenser (Q_{cond}) are calculated according to equations (1) and (2), respectively, while total energy exchanged for each component (EE_{ADS}, EE_{cond}) is estimated with equations (3) and (4) integrating the heat transfer rate. Energy density per m^3 of silica gel is calculated according to equations (5) and (6) for the adsorbent reactor ($\dot{EE}_{ADS}$) and condenser ($\dot{EE}_{cond}$) respectively, considering a mass of 25 kg of silica gel within the reactor (M_{ADS}) and a reference density (ρ) of 700 kg/m^3 for standard RD silica gel. Experimental tests were conducted considering a discharging phase with an inlet evaporator temperature of 20 °C, $T_{ads,in}$ of 30 °C, and flowrate of 0.4 m^3/h on both components. For the charging phase, $T_{ads,in}$ was set to 90 °C and $T_{cond,in}$ to 30 °C. The test was at first carried out with the valves connecting the bed with condenser and adsorber completely open during the respective process (base case). Then, a second test has been done regulating the aperture of the valves to study the influence of the water vapour flow on the overall process. Comparison between results with valves totally and partially open are presented in Figure 2 for the discharging phase and in Figure 3 for the charging stage.

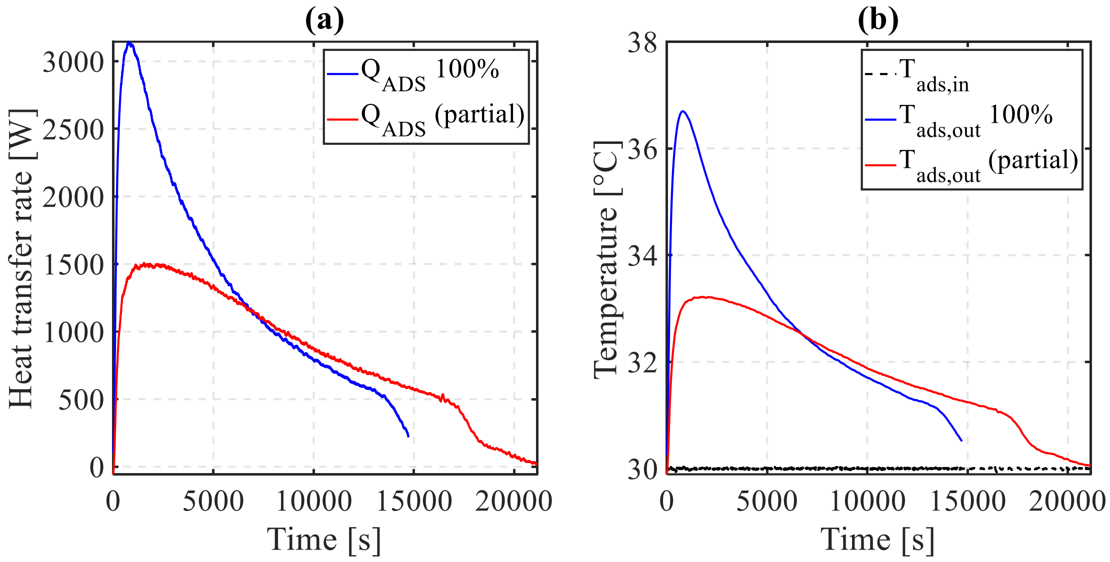

Figure 2. Adsorption reactor discharge phase results with valve fully opened (100%) and partial aperture: (a) Q_{ADS} (b) Temperature profiles

As seen in Figure 2, the discharging phase had a duration of 4 hours for the base case, with a total exchanged energy on the adsorption reactor equal to 19.6 MJ. For the adsorption reactor, the calculated energy density was of 152 kWh/m^3. By reducing the vapour flow, the test's duration had a 46% increase with respect to the base case, allowing to obtain a longer period of relatively stable outputs, as seen in Figures 2a and 2b. Corresponding peak power in the adsorption reactor is reduced to 1500 W (a decrease of 52% compared to the base case). Considering the peak temperature difference (see Figure 2b) it is reduced from 6.71°C to 3.25°C (51% decrease). Even though exchanged energy values are in the same range compared to the base case, the achieved results demonstrate that the vapour flow variation is a parameter that can help to optimize the management strategy of the single-bed adsorption unit for heat storage applications. Regarding the charging phase (see Figure 3), the duration of the base case was 03:48 hours, with a total exchanged energy for the condenser and adsorption reactor of 21 and 19.6 MJ, respectively. Peak power from the condenser and adsorption reactor were, respectively, 13 and 7.3 kW. When reducing the water vapour flow, peak power in both the condenser and adsorption reactor had a reduction of 12% and 6% respectively, with an increase of 23% in phase duration. Obtained energy density of the condenser was of 170 kWh/m^3. Considering the high driving force enabling the desorption phase (due to a higher pressure difference between reactor and condenser), the valve would need to be further partially closed to limit even more the flowrate of desorbed vapor and produce smoother outputs like those of the discharging stage. This leads to the conclusion that future activities can be focused on improving/optimizing the cooling effect and thermal energy storage potential during the discharging stage. These improvements can be done by changing also other parameters, such as pump's flowrates, the falling-film system setting, and temperature levels in each component.

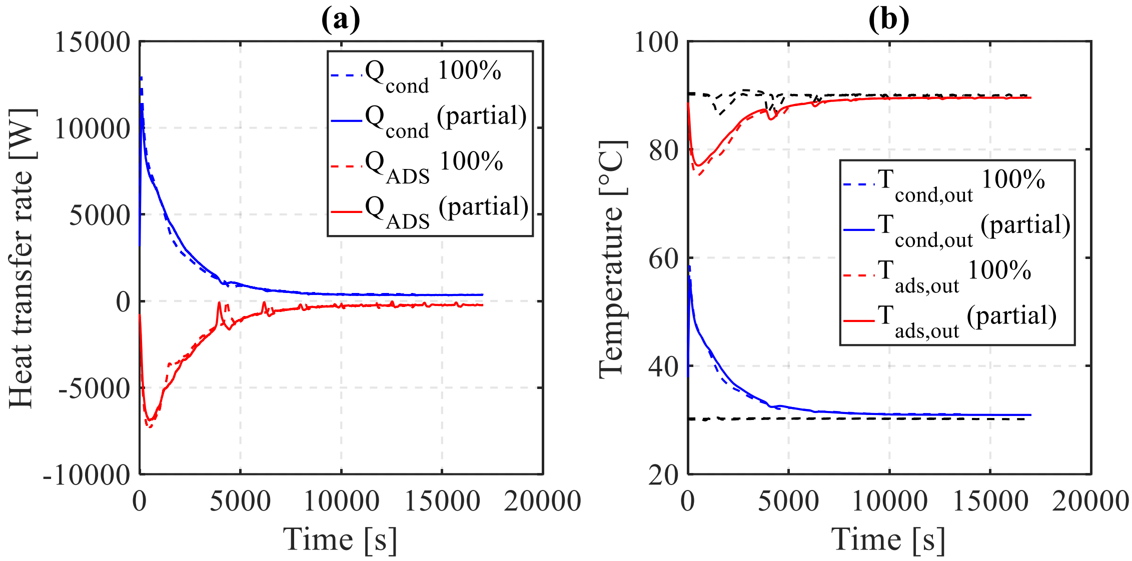

Figure 3. Desorption/condensation results with valve fully opened (100%) and partial aperture: (a) Q_{cond} and Q_{ADS} (b) T_{cond} and T_{ads} temperature profiles

Summary/Conclusions

- Testing the discharging phase with inlet evaporator temperature of 20 °C, $T_{ads,in}$ of 30 °C, and flowrate of 0.4 m^3/h produced a discharging phase that lasted 4 hours, with the exchanged energy on the adsorption reactor equal to 19.6 MJ (152 kWh/m^3).
- During the charging phase with $T_{ads,in}$ set to 90 °C and $T_{cond,in}$ to 30 °C (flowrate of 0.4 m^3/h on both components), the test lasted for 03:48 hours with peak power on the adsorption reactor and condenser equal to 13 and 7.3 kW, respectively.
- Limiting the refrigerant flowrate with the valve's partial aperture allowed to have a 46% increase of the duration of the discharging phase, and a reduction of 50% on the peak power and maximum temperature difference on the adsorber reactor.
- Peak power in both the condenser and adsorption reactor had a respective reduction of 12% and 6% during the charging phase, concluding that this phase requires the valve to be further closed to smooth the heat transfer rate and temperature profiles.

References

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