Water vapor adsorption in silica gel for thermal energy storage application

Ye Hua, Amanda Godin, F. Handan Tezel*

Department of Chemical and Biological Engineering, University of Ottawa, 161 Louis-Pasteur, Ottawa, Ontario K1N 6N5, Canada

*Corresponding author: Tel: (+1) 613-562-5800; E-mail: Handan.Tezel@uottawa.ca

DOI: 10.5185/amlett.2019.2181
www.vbripress.com/aml

Abstract

Thermal energy storage (TES) by water vapor adsorption process has attracted increasing interest for its thermal applications such as space heating and cooling. However, the experimental energy density of the adsorbents may vary as the operating system and conditions change, which could be much lower than the theoretical energy density. In this manuscript, an experimental system has been designed and built to examine the effects of the regeneration temperature and relative humidity (RH) on a commercial silica gel material's performance as adsorption TES material. The experimental energy density under different operating conditions were calculated. Up to 25 adsorption-desorption cycles were performed to examine the stability of the material and the repeatability of the results. Copyright © 2019 VBRI Press.

Keywords: Thermal energy storage, water vapor adsorption, energy density, breakthrough tests.

Introduction

The energy system around the world is facing technology transformation. The deployment of renewable energy generation and the development of new clean technologies offer the opportunities to diversify energy supply, improve energy independence and reduce greenhouse gas emissions [**1-2**].

Although it is environmentally beneficial to use renewable energy in the electricity production, heating purpose and transportation, one of the main difficulties faced by the energy industry is the absence of economic and reliable energy storage solutions [**3**]. Most of the renewable energy supply can only generate relatively fixed amount of energy over short periods of time, while the energy demand varies in a daily, weekly, seasonal basis. Therefore, developing technology to store energy for it to be available at any time is essential for the energy system development.

Energy can be stored in many forms: mechanical, chemical, electrochemical, biological, magnetic, and thermal [**4**]. Thermal energy storage (TES) provides an alternative method to store energy generated from different types of energy sources (traditional or renewable) and correct for the mismatch between the energy supply and demand.

Among various TES methods, one of the most novel processes is adsorption. The adsorption TES process consists of two steps: adsorption and regeneration (desorption). It uses the exothermic adsorption step to release the energy (discharging) and the endothermic regeneration (desorption) step to store the energy (charging).

The adsorption TES technology has three major advantages compared to other energy storage methods: (1) Low environmental impacts: no toxic compounds or chemicals are used in the process, which minimize the risk of chemical leaking and pollution; (2) The adsorption process is fully reversible, which results in the high energy efficiency of the adsorption TES system; (3) The energy can be stored inside the material forever: the thermal energy is stored in the system in the form of chemical potential (heat of adsorption). Unlike latent or sensible heat storage, there is no heat loss due to the temperature differences between the system and the surrounding environment during the storage period. Therefore, minimum thermal insulation is required for the heat storage of the adsorption TES system.

Silica gel has been widely used as a desiccant for decades [**5**]. Its physical properties and the water vapor adsorption behavior in packed bed has been well studied by many researchers [**5-8**]. However, only a few studies have been carried out on its thermal properties [**9-11**] and adsorption TES applications [**12-14**]. D. Zhu *et al.* reported the TES capacity of 47 kWh/m^3 for pure silica gel adsorbent and 224 kWh/m^3 for a composite silica gel supported $CaCl_2$ sorbent by impregnating silica gel with the hygroscopic salt $CaCl_2$ using 90 ^oC charging temperature (referred as the regeneration temperature in this study) and 80% relative humidity operating condition [**13**]. However, no studies have been reported on silica gel material's TES performances under different operating conditions.

In this paper, a bench scale experimental set-up was introduced and used to test the selected thermal energy storage materials. Various experimental conditions with different regeneration temperature and relative humidity were used to simulate the real-life operating conditions. The amount of energy released during the adsorption process and the experimental energy densities at each condition were calculated based on the experimental data.

Experimental

The silica gel adsorbent material was provided by XEBEC Adsorption Ltd. (Blainville, Québec, Canada). A thermal energy storage experimental system using packed bed adsorption column was built in our lab (see **Fig. 1**) by modifying the system used by Lefebvre *et al.* [**15**].

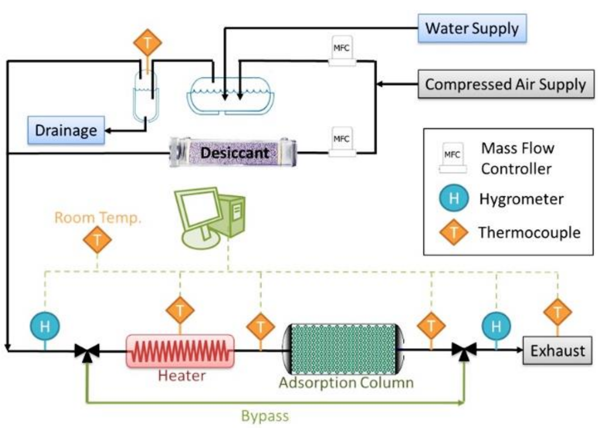

Fig. 1. Schematic illustration of the adsorption thermal energy storage system.

Compressed air provided by the research facility first passes through an oil filter to remove any impurities before connecting to the dry and wet streams. Mass flow controllers (MFC) are installed at the upstream of the dry and wet air streams to control the flow rate of air through each stream. The dry air stream passes a drying column filled with desiccants to remove moisture in the air, and the relative humidity (RH) of the dry air stream is controlled within less than 2%. The wet air stream first passes through a humidifier, where an ultrasonic fogger was installed inside, to generate moist air with RH up to 96%. By adjusting the flow rates of the dry and wet air streams, a moist air mixture with desired flow rate and RH can be obtained. A total flow rate of 24 standard liter per minute (SLPM) were used in all breakthrough experiments based on our group's previous research [**15**].

The moist air mixture passes through an electrical heater and the adsorption column before exhausting out of the system. A by-pass was built to avoid any undesired air flow through the heater and the adsorption column during the experiments.

Thermocouples were installed along the system to measure temperature of the air stream at selected points. The wet air temperature, the heater skin temperature, the inlet and outlet air stream temperatures of the adsorption column, the exhaust air temperature and the room temperature of the lab are recorded every 10 seconds during each experiment.

Hygrometers were installed before and after the heater, column and the by-pass section to monitor the RH and temperature of the moist air mixture.

A system control program is designed to control the experimental system and record the data using LabVIEW system design platform.

Adsorbent material was packed in the adsorption column. The adsorbent size and properties of the adsorption column are presented in **Table 1**. Experiments were performed at selected range of flow rate, relative humidity and regeneration temperature to examine the effect of the operating condition on the experimental energy density.

Table 1. Silica gel adsorbent size and adsorption column properties.

Properties	Values
Adsorbent pellet size	8 – 12 US mesh
Adsorbent pellet diameter	1.68 – 2.38 mm
Column length	6.9 cm
Column inner diameter	3.4 cm
Column outer diameter	3.8 cm
Column volume	62.8 cm^3

Each cycle of the experiment consists of three steps: the regeneration; the RH set-up and the adsorption.

(i) During the regeneration step, dry air was heated up by passing through the heater to a preset temperature before entering the packed column. The dry warm air activated and dried the silica gel inside the column by liberating the pore sites from any residual water. The regeneration step was completed when the RH of the air at the column outlet was close to zero (less than 2% RH). With this regeneration step, the thermal energy storage material silica gel was charged with energy. In this study, regeneration temperature range of 80-120 °C was used in the experiments to mimic the span of deliverable solar vacuum tube collector temperatures.

(ii) The next step (RH set-up step) was to prepare the moist air mixture at desired RH for the adsorption experiments. When the column and the adsorption material are cooled down to room temperature after regeneration, the three-way valve was switched to direct the air flow to the by-pass pathway. By adjusting the flow rate and the mass flow ratio of the dry and wet air streams, a moist air mixture with desired flow rate and RH (as high as 96%) can be obtained. Once a stable moist air flow was achieved, the three-way valve would close the by-pass pathway and direct the moist air mixture to the packed column pathway to start the adsorption process.

(iii) During the adsorption step, the silica gel material adsorbs the moisture in the moist air mixture and the stored energy was released due to heat of adsorption, which heated up the air carrying the moisture. The temperature and RH of the air mixture at the inlet and outlet of the column were recorded by the LabVIEW program as a function of time. The adsorption process was completed when the inlet and outlet column temperatures were equal and the outlet RH reached inlet RH, indicating that the adsorbent was saturated.

Cyclic breakthrough experiments were also carried out to determine the energy density and stability of the adsorbent material under selected regeneration temperature range.

Results and discussion

Regeneration temperature range of 80-120 °C and inlet air stream RH of 10%, 30% 50% were used in the breakthrough experiments to compare the experimental energy density of silica gel packed bed at selected operating conditions. A total flow rate of 24 standard liter per minute (SLPM) were used in all breakthrough experiments. A typical breakthrough curve for RH and temperature using 100 ºC regeneration temperature and 50% inlet RH are shown in **Fig. 2**.

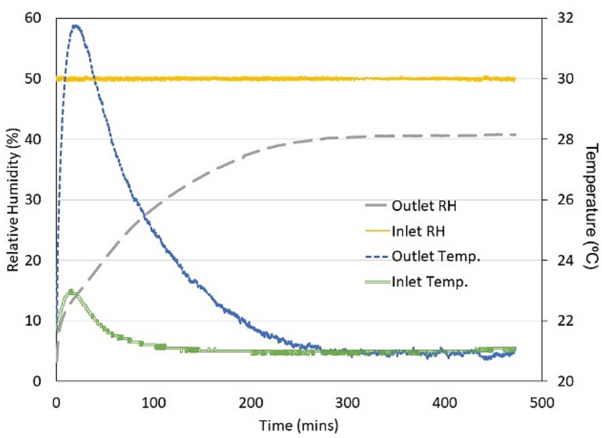

Fig. 2. Relative humidity and temperature breakthrough curves for silica gel packed column using 100ºC regeneration temperature and 50% inlet RH.

As demonstrated in **Fig. 2**, due to the high flow rate (24 SLPM) and relatively short column length (6.9 cm), the water vapor broke through immediately after the adsorption started. The complete adsorption equilibrium inside the packed column was reached after about 5 hours (300 minutes). A discrepancy between the inlet and outlet RH was observed due to the possible condensation inside the column tubing and the pressure drop between the two hygrometer measuring points. Similar discrepancy was observed in all concentration breakthrough curves with different inlet RH. The actual RH the adsorbent was exposed to inside the adsorption column between the inlet and the outlet, would change between these RH values. Therefore, the average of the inlet and outlet RH values was used for data analysis of this adsorption process.

The stored thermal energy was released simultaneously during the adsorption process, which was demonstrated in the temperature breakthrough curves (see **Fig. 2**). The temperature differences between the column outlet and inlet air vary between 8 to 12 ºC depending on the operating conditions.

The energy density for each experiment can be calculated from the concentration (RH) and temperature breakthrough curves using Eq. (1):

$$Energy\ Density = \frac{\int_0^t (Um \times Cp \times \Delta T)\, dt}{V} \qquad (1)$$

where, *Um* is the mass flow rate (kg/s) of the moist air passed through the column, which can be calculated from the wet and dry air volumetric flow rate measured by MFCs using ideal gas law and the concentration; *Cp* is the heat capacity of the moist air (kJ/kg•K) inside the packed bed column; ΔT is the temperature difference (K) between the column inlet and outlet obtained from the temperature data; and *V* is the volume of the packed bed column used in the experiments.

The calculated energy density of silica gel sample measured at different inlet RH using different regeneration temperature were given in **Fig. 3**. It is important to note that due to the difficulties to keep the inlet RH stable at low RH levels, the smaller temperature rises and the longer breakthrough time, less degree of accuracy can be obtained for experiments performed at low RH conditions.

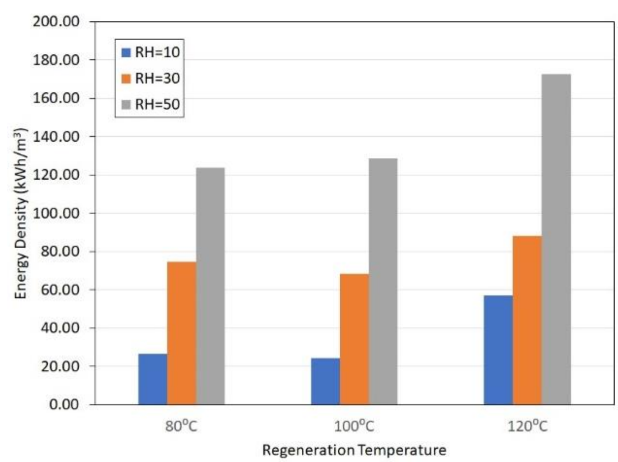

Fig. 3. Experimental energy density of silica gel sample measured at different inlet RHs and regeneration temperatures.

As demonstrated in **Fig. 3**, the experimental energy density increases with the increase in the inlet air RH. For regeneration temperature lower than 100 ºC, the impact of the regeneration temperature on the energy density is negligible. For regeneration temperature higher than 100 ºC, the experimental energy density increases with the increase in the regeneration temperature. In this study, the highest regeneration applied was 120 ºC, which is the highest regeneration temperature used in industry for silica gel without sample degradation.

The highest energy density of 172.48 kWh/m^3 was obtained with the highest regeneration temperature (120 ºC) and the highest inlet RH (50% RH) among the selected operating conditions: about 38.99 kJ of energy was released during the adsorption process using 62.8cm^3 silica gel sample.

Multi-cycle breakthrough experiments were also performed to determine the stability of the adsorbent material. Up to 25 cycles were carried out with different inlet air RH, each cycle mimicking the real-life operating situation as the RH of the air varies daily. Different regeneration temperatures were used as the amount of heat available to regenerate the TES material from the connected renewable energy sources fluctuates.

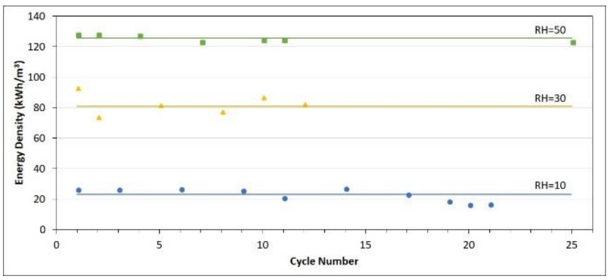

Fig. 4. Experimental energy density of multi-cycle breakthrough experiments using 80 ºC regeneration temperature for different inlet RH.

Fig. 4 summarizes the experimental energy density obtained using 80 ºC regeneration temperature and different inlet RH during the multi-cycle breakthrough experiments. As demonstrated in this figure, with 80 ºC regeneration temperature, the energy densities were stable at 23.01 kWh/m^3, 80.94 kWh/m^3 and 125.76 kWh/m^3 for inlet RH of 10%, 30% and 50% operating conditions, respectively. No sample degradation was observed after the experiments. Results obtained at other regeneration temperature showed the same trend.

Conclusion

Commercial pure silica gel adsorbent was tested to examine their performance of water vapor adsorption for thermal energy storage application. High energy density of 172.48 kWh/m^3 can be achieved at 120 ºC regeneration temperature and inlet moist air of 50% RH operating condition. Increasing the regeneration temperature and the RH of the inlet moist air increases the experimental energy density of the samples.

This specific silica gel adsorbent showed competitive energy density for TES application compared to other available adsorbent materials (e.g. zeolite 13X and activated alumina [**16-17**]) with much lower regeneration temperature and inlet air RH. It has the potential to provide an adsorbent material option for the development of residential TES system combinable with renewable energy sources such as solar panel.

Acknowledgements

Special thanks to XEBEC Adsorption Ltd. for providing the silica gel sample. The authors also would like to thank the Natural Sciences and Engineering Research Council of Canada (NSERC) for the financial support of this project through the NSERC Energy Storage Technology (NEST) Network.

Author's contributions

Conceived the plan: AG, YH and FHT; Performed the expeirments: AG and YH; Data analysis: AG, YH and FHT; Wrote the paper: YH and FHT. Authors have no competing financial interests.

References

1. Moreno, B.; López, A. J.; *Renewable Sustainable Energy Rev.*, **2008**, *12*, 732.
DOI : 10.1016/j.rser.2006.10.011
2. Rio, P. del; Burguillo, M.; *Renewable Sustainable Energy Rev.*, **2008**, *12*, 1325.
DOI : 10.1016/j.rser.2007.03.004
3. Lehr, U.; Nitsch, J.; Kratzat, M.; Lutz, C.; Edler, D.; *Energy Policy*, **2008**, *36*, 108.
DOI : 10.1016/j.enpol.2007.09.004
4. Dincer, I.; Rosen, M., Thermal Energy Storage Systems and Applications; John Wiley & Sons Ltd.: UK, **2011**.
DOI: 10.1002/9780470970751
5. Pesaran, A.; Mills, A.; *Int. J. Heat Mass Transfer*, **1987**, *30*, 1037.
DOI: 10.1016/0017-9310(87)90035-4
6. Chang, K. Sen; Wang, H. C.; Chung, T. W.; *Applied Thermal Engineering*, **2004**, *24*, 735.
DOI: 10.1016/j.applthermaleng.2003.11.003
7. Ng, K. C.; Chua, H. T.; Chung, C. Y.; Loke, C. H.; Kashiwagi, T.; Akisawa, A.; Saha, B. B.; *Applied Thermal Engineering*, **2001**, *21*, 1631.
DOI: 10.1016/S1359-4311(01)00039-4
8. Pesaran, A. A.; Mills, A. F.; *Int. J. Heat Mass Transfer*, **1987**, *30*, 1051.
DOI: 10.1016/0017-9310(87)90035-4
9. Ambrozek, B.; Zwaryez-Makles, W.; Szaflik, W.; *Polska Energetyka Słoneczna*, **2012**, 5.
10. Ramzy, A. K.; Kadoli, R.; Ashok Babu, T. P.; *Energy*, **2013**, *56*, 8.
DOI: 10.1016/j.energy.2013.03.048
11. Yamamoto, E.; Katsurayama, K.; Watanabe, F.; Matsuda, H.; Hasatani, M.; *Journal of Chemical Engineering of Japan*, **2000**, *33*, 12.
DOI: 10.1252/jcej.33.12
12. Jänchen, J.; Ackermann, D.; Stach, H.; Brösicke, W.; *Solar Energy*, **2004**, *76*, 339.
DOI: 10.1016/j.solener.2003.07.036
13. Zhu, D.; Wu, H.; Wang, S.; *Int. J. Therm. Sci.*, **2006**, *45*, 804.
DOI: 10.1016/j.ijthermalsci.2005.10.009
14. Gartler, G.; Jähnig, D.; Porkarthofer, G.; Wagner, W., Development of a High Energy Density Sorption Storage System, European Solar Conference (EuroSun 2004), Freiburg, Germany, **2004**. http://download.aee-intec.at/0uploads/dateien7.pdf.
15. Lefebvre, D.; Amyot, P.; Ugur, B.; Tezel, F. H.; *Ind. Eng. Chem. Res.* **2016**, *55*, 4760.
DOI: 10.1021/acs.iecr.5b04767
16. Lefebvre, D.; Tezel, F. H.; *Renew. Sustain. Energy Rev.* **2017**, *67*, 116.
DOI: 10.1016/j.rser.2016.08.019
17. Yu, N.; Wang, R. Z.; Wang, L. W.; *Prog. Energy Combust. Sci.* **2013**, *39*, 489.
DOI: 10.1016/j.pecs.2013.05.004

