

# EXPERIMENTAL ANALYSIS OF A ZEOLITE HEAT STORAGE SYSTEM

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**Abstract:** Solar energy supply does not always match demand and it is therefore necessary to investigate efficient ways of storing thermal energy. Sorption based thermochemical heat storage provides high energy densities as well as an exceptional advantage in minimizing losses when utilised for long-term heat storage. To commercialize sorption storage systems, additional research and development is required to validate numerical models to allow for accurate design calculations. A lab-scale prototype was developed to analyse the thermal storage characteristics of zeolite 13X in an open (non-pressurised) sorption system. The experiments that were conducted involved a reversible reaction between a solid (zeolite 13X) and a gas (water vapour in air). Two charging (desorption) processes were conducted, where the zeolite pellets were dehydrated by hot air at 130 °C and 200 °C respectively. During the two corresponding discharging (adsorption) tests, humidified ambient air was supplied to the reactor bed, which rehydrated the zeolite particles, resulting in a temperature increase of between 28-38 °C. The results obtained from this experimental work will be used to inform the design of a sorption heat storage system for a solar thermal plant.

*Keywords: Adsorption, Zeolite 13X, Water, Thermochemical Heat Storage*

## 1. Introduction

Global industrial development over the past century has largely relied on the combustion fossil fuels, which has resulted in the release of a large amount of CO<sub>2</sub> gas and other toxins, which are harmful to the environment. There is therefore, an urgent need to establish eco-friendly and cost-effective processes to reduce the reliance on fossil fuels and energy consumption in industry [1].

Thermal energy is the dominant energy end-use in industry, accounting for an estimated two thirds of demand [2]. Direct solar thermal integration into existing industrial heating systems has the potential to reduce the direct consumption of fossil fuels.

Since solar energy supply does not always match demand, Thermal energy storage (TES) has been identified as critical in these systems. Among the different TES methods, sorption (adsorption and absorption) heat storage is promising compared to conventional sensible TES and latent TES. Sorption TES can provide high energy density and can store energy long periods of time and can offer both heat storage and cold storage functions [3]. Water is the most feasible sorbent in open and closed systems due to safety, cost and availability. Typical physical water sorption materials include silica gel [4], zeolites [5], silicoaluminophosphates (SAPOs) and metal-organic frameworks (MOFs) [6].

Zeolites are traditionally referred to as a family of open-framework aluminosilicate materials consisting of orderly distributed micropores in molecular dimensions, they have high hydrothermal stability and low production costs making them a good candidate for TES [7]. The TES in Zeolites is based on adsorption, which involves the attachment of gas molecules to the surface of a solid. This process differs from absorption, which involves the bonding of gas molecules to a liquid. The substance that is adsorbed is called the adsorbate. The adsorbate enters the pores of the adsorbent and a chemical bond is formed which releases energy as a result (refer to Figure 1). When the pores are saturated, no further heat is released. The system can then be regenerated by heating the adsorbent to a suitable temperature to break the bonds between the adsorbent and adsorbate. This is an endothermic process and can also be referred to as desorption. Once the system has been regenerated, the adsorption process can be repeated. [8]

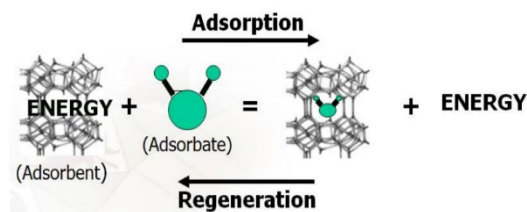
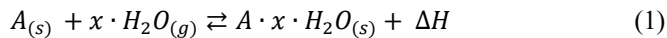


Figure 1. Adsorption and desorption processes [8]

The charging (adsorption) and discharging (regeneration) process for Zeolite 13X-Water is represented in equation 1 where  $A_{(s)}$  represents the zeolite 13X (solid),  $H_2O_{(g)}$  represents water vapour in air and  $\Delta H$  represents heat of adsorption or hydration. [9]



A prototype using zeolite 13X (40 kg) and water vapour as the adsorbent-adsorbate pair was developed by [10]. The reactor was charged at temperatures between 120 and 180 °C. During the discharge cycle, an average temperature increase of 38 °C was achieved at the outlet of the reactor for a period of 8 h. The inlet humidity was 10 g<sub>w</sub>/kg<sub>da</sub> and the flow rate was 180 m<sup>3</sup>/h. A revolving reactor was developed by [11] to minimise non-reactive zones. The maximum power delivered was 1.5 kW and the maximum temperature lift achieved at the outlet of the reactor was 60 °C. ZAE Bayern developed two mobile sorption storage systems of 14 tons in Germany. The zeolite-13X was regenerated at 130 °C with air from an industrial waste heat stream and discharged with moist air at 60 °C [12].

The purpose of this paper is to demonstrate the capability of zeolite 13X (adsorbent) for solar thermal storage in a Southern African context since most previous studies were conducted internationally. The adsorbate was water vapour in humid air. The system was regenerated at two different temperatures i.e. 130 °C and 200 °C, using an electric heater, and the results (from the adsorption and regeneration/desorption tests) are presented and compared. Lower temperatures in the vicinity of 130 °C are achievable by non-concentrating solar collectors such as evacuated tube collectors which have an operating temperature between 50 and 200 °C [13]. For higher temperatures (around 200 °C) concentrating solar collectors such as parabolic troughs will be required which can operate between 60 and 300 °C [13].

## 2. Experimental Apparatus

A packed bed thermal storage rig was designed and developed at the Council for Scientific and Industrial Research (CSIR). The major components include a centrifugal blower, electric heater, steam humidifier and packed bed reactor. Two configurations are illustrated, one for charging (Figure 2) and one for discharging (Figure 3) the packed bed. The components bordered by the dashed lines are repositioned for the charging and discharging cycle.

For the charging/ desorption cycle, the blower draws in air from the environment, through the conical inlet flow meter. The pressure differential at the throat of the conical inlet is measured to determine the mass flow through the rig. The air is then heated by the electric heater where the temperature is increased to between 130 °C to 200 °C. The arrows in Figure 2, represent the flow path of the air moving through the system. Blue is representative of

ambient air while red is representative of hot air. The hot air, exiting the electric heater, is supplied to the packed bed reactor. This leads to the breakage of the bonds between the adsorbent (zeolite 13X) and adsorbate (water vapour), resulting in the dehydration of the zeolite particles. As a consequence, hot humid air is exhausted to the environment from the outlet of the reactor.

The cylindrical packed bed reactor has a diameter of 400 mm and a height of 620 mm. A diffuser is attached to the inlet of the packed bed to distribute the air more evenly. A nozzle is attached to the exit of the packed bed to allow a smoother flow of air through the rig. The reactor comprises of several thermocouple ports to determine the temperature profiles through the packed bed. The thermocouples were positioned at approximately 100 mm increments along the axis of the reactor. The exact positions of the thermocouples are illustrated in Figure 4

Relative humidity sensors are positioned at the inlet and outlet of the rig, to monitor the temperature and humidity entering and leaving the reactor. To minimise heat losses to the environment, the reactor wall is insulated with a ceramic fibre blanket of 75 mm thickness.

For the discharging cycle (refer to Figure 3), the electric heater is repositioned (i.e. from main air stream) and connected directly to the steam humidifier. A second blower is added to the system to provide air supply to the electric heater. The humidifier is a basic heat exchanger (shell and tube). The electric heater transfers heat from air (in the shell) to water in the tube of the humidifier. The humidifier starts producing steam, as the boiling point of the water is approached, which is added to the air entering the reactor. The zeolite particles adsorb the water vapour from the humid air and release the heat stored. The flow path of the air through the system is illustrated by arrows in Figure 3.

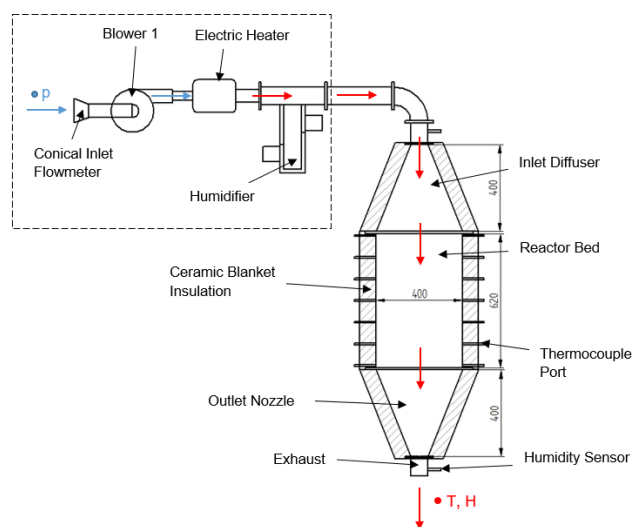


Figure 2. Diagram of rig showing charging configuration

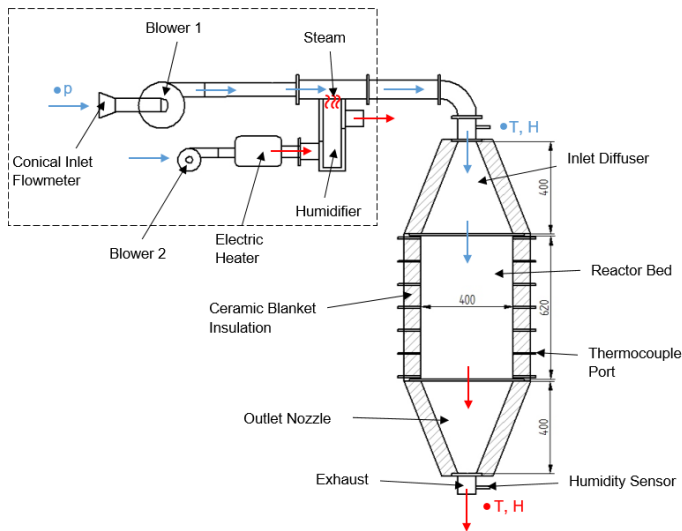


Figure 3. Diagram of rig showing discharging configuration

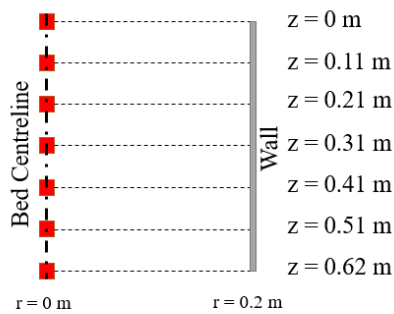


Figure 4. Thermocouple Locations in packed bed reactor

### 3. Results

Two charging (desorption) cycles and two discharging (adsorption) tests are presented in this paper that are representative of a solar thermal system. For the first charging test, the bed was heated to a temperature of approximately 130 °C and for the second charging test the bed was heated to a temperature of approximately 200 °C. The 130 °C temperature could be achieved using non-concentrating collectors, whilst concentration would be required to reach 200 °C. The corresponding discharging cycles are presented and discussed.

#### 3.1. Charging Cycle 1 (130 °C)

The temperature profiles (at the centre of the reactor) for the first charging test are presented in Figure 5. The temperature of the inlet air was raised to 130 °C by the electric heater. At the beginning of the cycle, the top layers of zeolite were heated by the inlet air stream, resulting in the desorption of water vapour. The cooler zeolite particles at lower levels in the bed reabsorbed

the water vapour from the high humidity air stream. This resulted in an increase in the temperature of the packed bed exit to 35 °C up until a time of  $t=1.6$ h. As the thermocline moved through the bed, subsequent layers of Zeolite underwent the desorption of water vapour, until eventually the entire packed bed was regenerated and the exit temperature ( $z=0.62$  m) was raised to 130 °C. The regeneration cycle lasted for 6 hours. The results are consistent with [14] in terms of the profile shape and duration of the cycle taking into consideration that their charging temperature was slightly higher at 150 °C

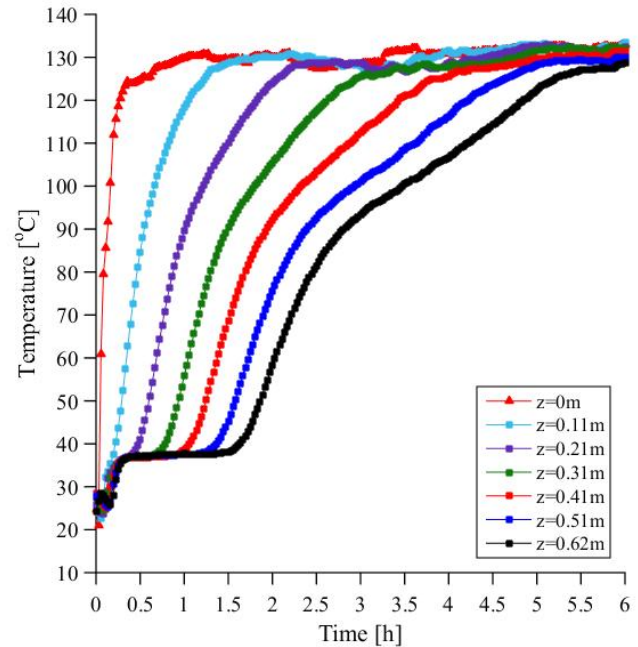
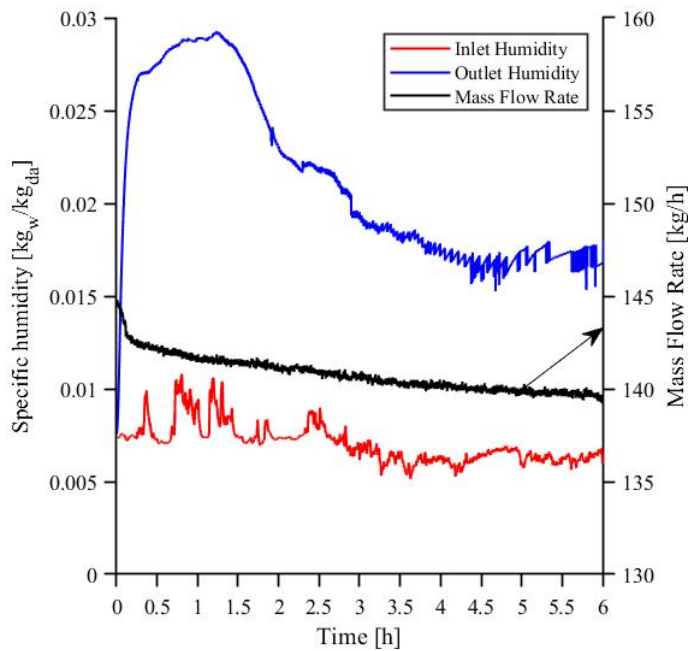


Figure 5. Temperature profiles for charging cycle 1

The specific humidity and mass flow rate results for charging cycle 1 are presented in Figure 6. The inlet (ambient) humidity range was between 5-10  $g_w/kg_{da}$  for the entire cycle. The maximum outlet humidity was 30  $g_w/kg_{da}$ . The outlet humidity decreased as the bed dried. The outlet humidity should agree with the inlet humidity at the end of the test as no more water is being desorbed. However, the humidity sensors are not accurate at temperatures above 100 °C due to the reduced scale of relative humidity in this temperature range. According to [15] the specific humidity is  $\pm 10\%$  accurate at a temperature of 150 °C. The average mass flow rate was 142 kg/h for the cycle and varied by 2% during the test.

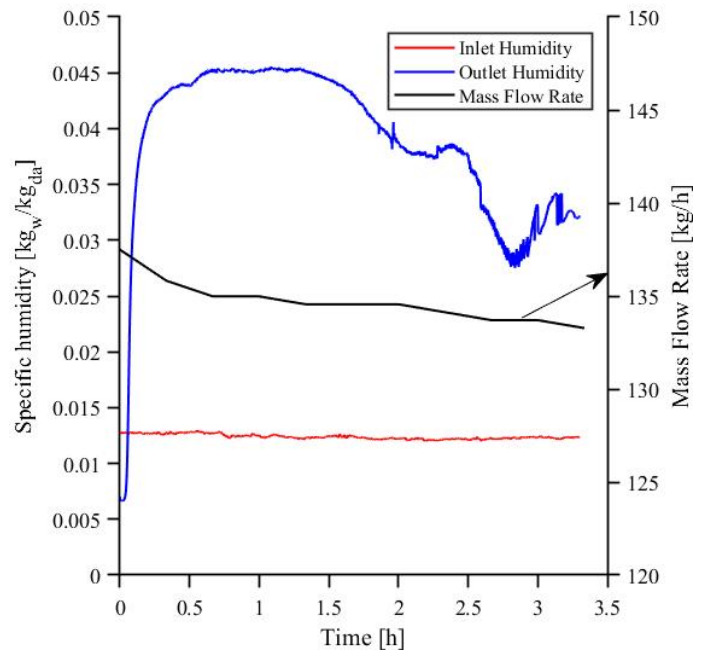
#### 3.2. Charging Cycle 2 (200 °C)

The temperature profiles for the second charging test are presented in Figure 7. The inlet temperature was raised to 200 °C for this cycle. The time taken to complete the cycle was 3.5 hours which was significantly lower than 6 hours for the first test. This shows that a higher temperature greatly influences the



**Figure 6. Humidity and flow rate for charging cycle 1**

regeneration time. The results are similar to [14] in terms of the profile shape and duration of the cycle taking into consideration that their charging temperature was slightly lower at 180 °C.



**Figure 8. Humidity and flow rate for charging cycle 2**

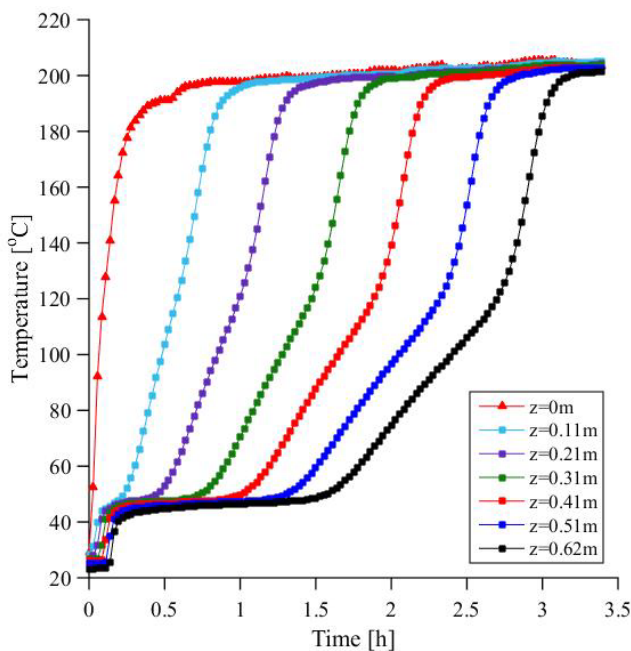
The humidity started to decrease from 90 minutes, since approximately half the bed was dry, and continued to decrease to 27 g<sub>w</sub>/kg<sub>da</sub> around the 3-hour mark. Thereafter it started to increase before levelling off at around 33 g<sub>w</sub>/kg<sub>da</sub> towards the end of the test. The outlet humidity should continue to decrease (from 90 minutes) as the bed dries.

However, the relative humidity sensor becomes less accurate as the temperature increases above 100 °C. This can be observed as the outlet temperature starts to rapidly increase around the 3-hour mark and at the same time the outlet humidity starts to increase. According to [15] the specific humidity is ±34% accurate at a temperature of 200 °C. The average mass flow rate was 135 kg/h for the cycle and varied by 2% during the cycle.

### 3.3. Discharging Cycle 1

The temperature profiles at the centre of the reactor are presented in Figure 9. Ambient air was supplied to the inlet of the reactor at approximately 33 °C. The maximum temperature realised at the outlet of the reactor was 61 °C which is a temperature increase of approximately 28 °C across the reactor. The cycle lasted for almost 8 hours. The adsorption occurred at the upper layers of zeolite first before proceeding to the next layer below it. This can be clearly seen on the graph as the bed cools down to ambient at different times indicating that adsorption is complete on that layer.

It took approximately 30 min for the outlet of the bed to heat up. Initially, the heat at the outlet ( $z = 0.62$  m) is due to sensible heat



**Figure 7. Temperature profiles for charging Cycle 2**

The specific humidity and mass flow rate results for charging cycle 2 are presented in Figure 8. The maximum humidity at the outlet was 45 g<sub>w</sub>/kg<sub>da</sub>, which was higher than charging cycle 1.



that is transferred from the upper layers until finally the adsorption reaches the lowest layer, i.e. closest to the outlet. Once adsorption is complete on the lowest layer the outlet cools down to ambient indicating that all the heat stored has been discharged.

The humidity and mass flow rate results are presented in Figure 10. The test was conducted on a very dry day. The inlet humidity at the start of the test was approximately 9 g<sub>w</sub>/kg<sub>da</sub> before decreasing to 5 g<sub>w</sub>/kg<sub>da</sub> at the end of the test which is relatively low. The outlet humidity was 0 g<sub>w</sub>/kg<sub>da</sub> for majority of the test since almost all the water entering the reactor was adsorbed by the zeolite pellets. Once the adsorption process nears completion the outlet humidity rapidly increases to match the inlet humidity since no more water is being adsorbed by the zeolite pellets. The average mass flow rate was 164 kg/h for the cycle and varied by approximately 2% during the test.

The results achieved are consistent with [14] where a temperature lift of 25 °C was realised after charging the bed to 120 °C and discharging it at a humidity of approximately 7 g<sub>w</sub>/kg<sub>da</sub> (50% RH at 20 degrees). The outlet temperature of approximately 60 °C is suitable for drying applications with the added benefit of approximately 0 g<sub>w</sub>/kg<sub>da</sub> humidity in the air after passing through the packed bed of zeolite.

### 3.4. Discharging Cycle 2

The temperature profiles are presented in Figure 11. The temperature increase was approximately 38 °C which was higher than discharge cycle 1 of 28 °C. The cycle was also approximately 30 minutes less than the first test. This is due to a slightly higher humidity supplied to the reactor and hence higher adsorption rate.

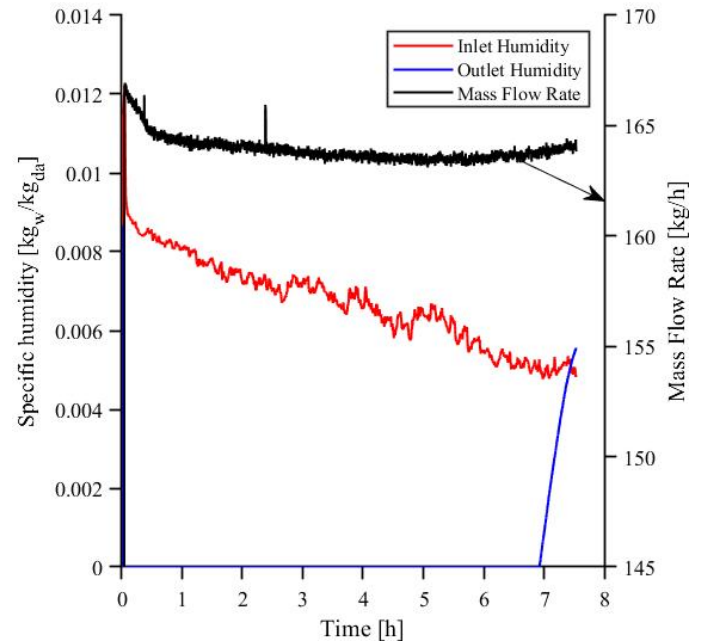


Figure 10. Humidity and flow rate for discharging cycle 1

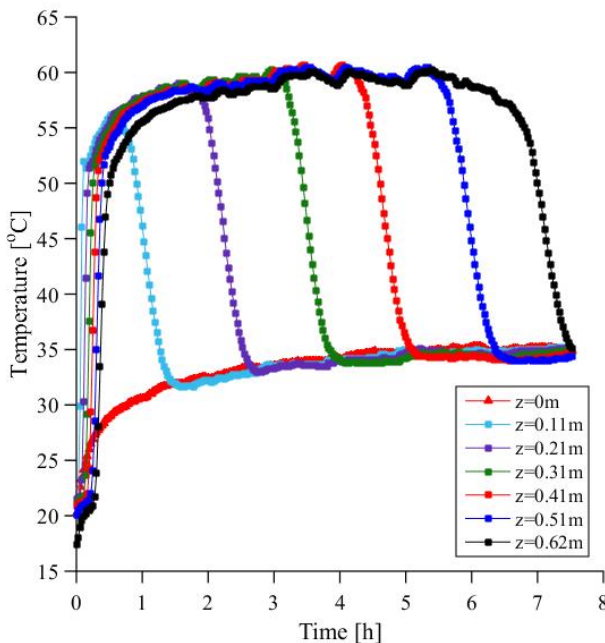


Figure 9. Temperature profiles for discharging cycle 1

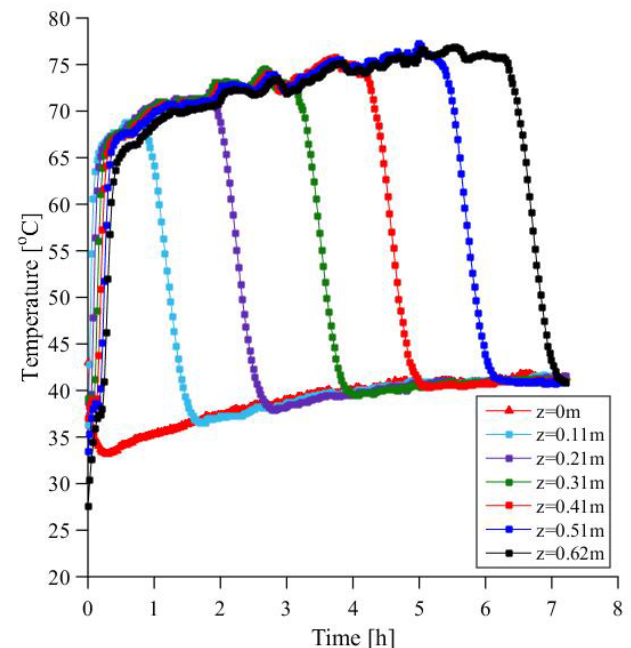
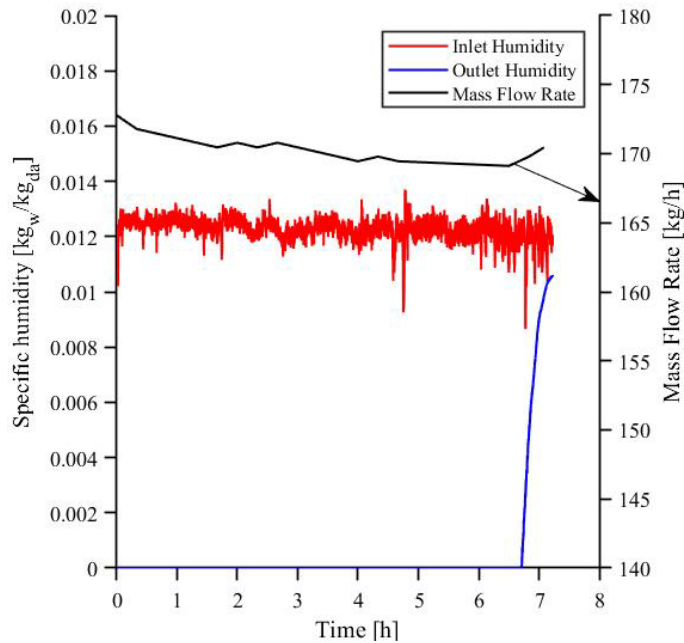


Figure 11. Temperature profiles for discharging cycle 2

The humidity and mass flow rate results are presented in Figure 12. The inlet humidity was maintained at approximately 12 g<sub>w</sub>/kg<sub>da</sub> for this test. This is slightly higher than the first test. The outlet humidity was 0 g<sub>w</sub>/kg<sub>da</sub> for majority of the test. It then rapidly increases to match the inlet humidity indicating that no more water is being adsorbed and the cycle is complete. The average mass flow rate was 170 kg/h for the cycle and varied by approximately 2%.



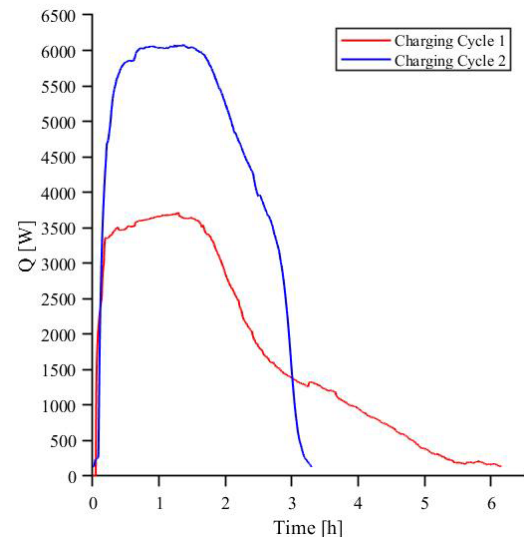
**Figure 12. Humidity and flow rate for discharging cycle 2**

The results achieved are consistent with [14] where a temperature lift of 37 °C was realised after charging the bed to 180 °C and discharging it at a humidity of approximately 10 g<sub>w</sub>/kg<sub>da</sub> (70% RH at 20 degrees). The outlet temperature of approximately 75 °C is also suitable for drying applications and can also be used for heating water or pre-heating combustion air.

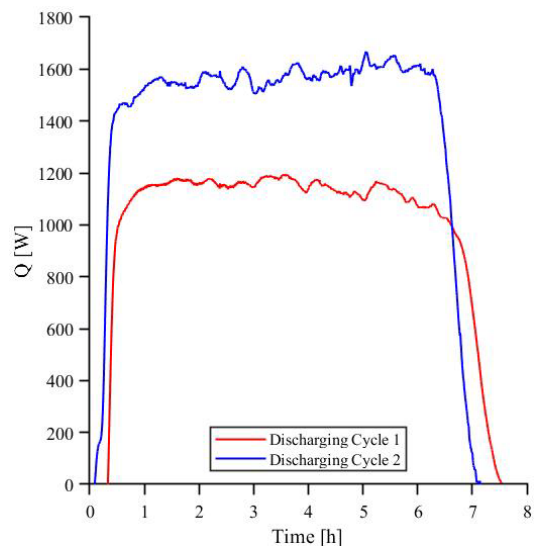
### 3.5. Energy Stored and Released

The energy stored during the two charging cycles is presented in Figure 13. A maximum of 3.7 kW was absorbed during charging cycle 1 and a maximum of 6.1 kW was absorbed during charging cycle 2. The total energy stored (based on the area under the curve) was 10.78 kWh and 14.93 kWh respectively.

The energy released during the two discharging cycles is presented in Figure 14. A maximum of 1.6 kW was released during charging cycle 1 and a maximum of 1.2 kW was released during charging cycle 2. The total energy discharged was 7.53 kWh and 10.03 kWh respectively. The overall energy efficiency for the two tests were 69.9% and 67.2% respectively. This agrees with the overall energy efficiency calculations done by [16] for an open sorption storage system.



**Figure 13: Energy stored in the reactor**



**Figure 14: Energy released from reactor**

## 4. Conclusion

Zeolite thermal storage has the potential to greatly improve the efficiency of existing industrial systems. The integration of zeolite thermal storage with solar energy can significantly reduce overall energy costs and carbon emissions. From the testing conducted it is evident that zeolite can be regenerated at temperatures as low as 130 °C which is achievable by solar thermal systems. The time taken to regenerate the packed bed was 6 hours at a temperature of 130 °C and 3.5 hours at a temperature of 200 °C. With regards to the discharge/ adsorption cycle, a temperature lift of 28 °C was realised across the reactor when it was regenerated at 130 °C whereas a temperature lift of 38 °C was observed across the reactor when it was regenerated at 200 °C. This is a difference of 10 °C between the two tests.

However, the humidity achieved at the inlet in the first cycle was significantly lower (approximately 4-6 g<sub>w</sub>/kg<sub>da</sub> less) than the second cycle. According to [9], the temperature increase across the reactor is a significant function of the humidity and this is the apparent reason for the deviation of 10 °C. The total energy released during discharging cycle 1 was 7.53 kW compared to 10.3 kW for discharging cycle 2. However, charging cycle 2 absorbed 4.1 more kW than charging cycle 1. The energy efficiency for the two tests were 69.9% and 67.2% respectively. It can be concluded that zeolite 13X can be regenerated at low temperatures (as low as 130 °C) with a similar efficiency achievable as higher regeneration temperatures. The next step of our work is to develop a solar thermal testing facility using evacuated tube solar collectors and demonstrate the efficiency of zeolite 13X for thermal storage in South African climatic conditions.

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