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Research Papers

Experimental parametric evaluation of adsorption characteristics for silica gel - water based open-bed system for seasonal thermal energy storage

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ABSTRACT

This study aims to investigate the potential of using commercial silica gel as an energy storage material in a bulk-scale open bed adsorption-based system to achieve efficient domestic heating using renewable energy sources. Designing an efficient thermal energy storage (TES) system for practical use requires understanding of the sorption properties of the adsorbent and the effects of different operating and physical parameters on the sorption process. One critical parameter that significantly affects the energy storage density when scaling up from a laboratory to a prototype system is the amount of adsorbent in the reactor. Surprisingly, this aspect has been overlooked in previous studies. To address this research gap, a laboratory-scale test rig was designed and constructed. This rig enables the evaluation of the effects of different operating parameters (such as relative humidity, flow rate, and regeneration temperature) and physical parameters (such as the quantity of adsorbent and particle diameter) on the energy storage density of silica gel and the temperature lift in the process. The water adsorption capacity of the silica gel was measured in-house to assist in future theoretical modelling of a prototype TES system. Optimum operating conditions were determined for the system, with a relative humidity of 80 %, an air flow rate of 100 L/min, and material regeneration at 120 °C. The system's performance in terms of material energy storage density and maximum temperature lift was observed for varying amounts of adsorbent, particle diameter, and regeneration temperature at these optimal operating conditions. Finally, the required storage volume to meet domestic space heating demands was estimated based on optimal discharging conditions and compared to other experimental and theoretical studies involving silica gel-based energy storage systems.

1. Introduction

The global energy technology industry is shifting toward sustainable energy sources such as solar, wind, and geothermal heat due to the depletion of non-renewable fossil fuels and the need to mitigate the effects of greenhouse gas emissions [1]. However, these renewable energy sources are often intermittent [2,3], leading to a mismatch between energy supply and demand. For example, solar energy is abundant during the daytime and summer months, while heat consumption is higher at night and during the winter. The solution to this problem is to store excess solar energy during the summer and discharge it during times of higher demand in the winter [4]. This has highlighted the importance of research and development of seasonal energy storage systems over the last two decades.

Thermal energy storage systems can be classified into three main types based on the storage method and media used: sensible heat, latent heat, and thermochemical heat [5]. Sensible heat storage involves increasing the temperature of a material (such as water, rock, or soil) using excess heat available at that time [6]. This type of heat storage is limited by the specific heat capacity of the material and the temperature difference used for storage, resulting in low energy density (~30 kWh/m^3) and considerable heat loss over time, making it unsuitable for seasonal heat storage [7]. Latent heat storage, on the other hand, involves the phase change (melting/solidification) of materials such as ice, paraffin, salts, fatty acids to store or release heat [8,9]. Although this method has higher energy densities, the phase change of materials can only occur at certain temperatures, making it difficult to attain that temperature solely from low-grade heat. Moreover, most of the suggested phase change materials in literature are toxic, corrosive, and chemically unstable for long-term heat storage [10,11]. Thermochemical energy storage involves chemical reactions or sorption processes that store heat as chemical potential [3,12–14]. These methods require heat to disintegrate two working substances, and heat is recovered through a reverse exothermic process. This technology is suitable for long-term seasonal storage as long as the working components are

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Nomenclature

a	parameter in sips isotherm (kPa)
C	adsorbed water (g)
C_0	maximum adsorbed water (g)
d	absolute humidity
H	enthalpy (joules)
$\dot{m}$	mass flow rate (kg/s)
M	mass (kg)
n	parameter in sips isotherm
P	pressure (kPa)
P_s	saturated vapor pressure (kPa)
Q	heat demand (kWh)
RH	relative humidity
t	time (s)
T	temperature (°C)
$\overline{UA}$	overall heat transfer coefficient (W/K)

Subscripts

ads	adsorbent
amb	ambient
f	fluid
exit	outlet of the reactor
inlet	inlet of the reactor
sh	space heating

separated. Theoretical studies suggest that chemical reactions provide the highest energy storage density [15], but these reactions generally depend on a catalyst to release heat and may not be practical for all applications [16]. This article will focus on adsorption-based energy storage technology due to its high energy density, non-toxic and non-reactive working materials, and long-term energy storage capabilities.

Water based adsorption-based TES systems can be designed as open or closed systems depending on their configuration. In a closed bed system, a solid sorbent and a water are kept in two evacuated containers that are isolated from each other [17]. Thermal energy from a renewable heat source is supplied to dissociate this working pair. In open bed systems [18], water moisture in the air is used as working gas. The required heat of desorption is transferred by hot air that flows through the solid adsorbent. In this case, air acts as the heat and mass transport medium during the charging and discharging processes. Both of these system configurations have their advantages and drawbacks, which have been extensively discussed in the literature [5,19]. Abedin and Rosen [20] investigated and compared the thermodynamic performance of two systems. Michel et al. [21] performed a sensitivity study and second law analysis using a 2D model to examine the performance and limitations of open and closed systems. The experimental study described in this article has chosen an open system due to its simpler design and requirement for fewer components compared to a closed system.

Selecting a suitable material for the application and making appropriate use of the available energy source are key factors for designing an adsorptive heat storage system. The selection criteria for adsorbent materials for solar energy storage applications have been listed in previous literature [3,22,23]. As water in the form of humidity in air is used as the adsorbate in an open bed system, common hydrophilic materials such as zeolites [24–26], activated alumina [27,28] and silica gel [29–31] have been widely studied. However, zeolite and activated alumina, with a high regeneration temperature of above 150 °C or even 200 °C, become disadvantageous for achieving a desirable energy density for existing renewable energy storage [11]. Alkaline salt needs to be impregnated into these porous host materials to enhance the energy storage density (ESD) by means of lowering the dehydration temperature [32]. Hauer [33] has compared zeolite and silica gel as thermal energy storage materials in terms of their equilibrium adsorption capacity and the nature of their breakthrough curves. This study concludes that the instability of zeolite at high temperature and high humidity during desorption makes it unsuitable for energy applications. A thermodynamic analysis conducted by Frazzica and Freni [34] has determined that zeolite is not efficient when solar collector is the primary energy source. In comparison, silica gel demonstrates promising potential as a suitable candidate for water adsorption capacity [35], energy storage density [36], and appropriate regeneration temperature (60–85 °C) [37,38], which calls for further research at the application level. The non-toxicity, chemical stability, repeatability, commercial availability, and cost-effectiveness of silica gel make it a lucrative option for demonstration scale long-term heat storage systems.

Numerous studies have been devoted to investigating the potential of silica gel and water as an adsorbent/adsorbate pair for energy storage systems over the past two decades. Tahat [29] proposed a simple closed bed experiment to analyse the feasibility of using silica gel as a heat storage material. The first prototype of a modular energy storage system using 200 kg of silica gel was developed for a single-family home in the MODESTORE project [38,39], which was able to produce a system energy density of 33 kWh/m^3. Fernandes et al. [40] conducted a theoretical study on the possibility of including a silica gel-filled adsorber in a solar hot water system as a thermal energy storage device. They noted the lack of a complete set of experimental data for the validation of a theoretical model in previous research. A thermal analysis of a system storing 18 kWh of heat was carried out [41] to estimate the amount of silica gel (350 kg) required at 25 °C evaporation temperature. Detailed experimental research was conducted by Lim et al. [30] on a lab-scale closed bed system using 1250 g of silica gel as a heat storage material. Their work revealed that higher evaporation temperature and the addition of a vapor transport system in the reactor have a positive effect on the energy storage process. Kant et al. [42] performed a theoretical study to design and optimization of heat storage performance of silica gel water base closed bed system. The degradation characteristics of 800 g of silica gel in terms of water adsorption capacity and energy density over five cycles were tested [43]. Heat storage density was found to decrease from 292 kJ/kg at the first cycle to 225 kJ/kg at the fifth cycle. Wang et al. [44] conducted experimental and numerical research to examine the discharging behaviour of a thermochemical reactor filled with 290 g of silica gel under various charging conditions and different flow directions. A researcher group at the University of Ottawa [31,45] presented an experimental parametric study to understand the effect of different operating parameters such as inlet humidity, flow rate, regeneration temperature, and particle size on system performance. For this purpose, a bench-scale open-cycle apparatus containing 50 g of silica gel was designed. Optimal conditions were defined as 90 % relative humidity, 120 °C regeneration temperature, and 24 SLPM flow rate, and an energy density of 200.7 kWh/m^3 was obtained under these conditions. Although this study provides a range of experimental data for the thermal performance of silica gel under different conditions, its limitation is the small amount of silica gel used in the process. The heat and mass transfer properties of the adsorbent-filled bed will vary widely when a practical heat storage system is designed with a significantly larger amount of material, which will have a significant effect on the energy storage performance of the material. Table 1 summarizes the studies previously conducted on silica gel/water – based energy storage systems.

The literature review clearly highlights the need for a thorough investigation into the thermal performance and adsorption capacity of silica gel to design an efficient energy storage prototype. A closer look at

Table 1
Summary of previous research on silica gel/ water - based energy storage system.

Ref.	Study	System Type	Size	Parameters	Performance observation
Tahat [29]	Experimental	Closed bed	–	–	Feasibility of using silica gel as heat storage material is examined.
Jähnig et al. [38]	Experimental	Closed bed	200 kg	–	First prototype of silica gel based closed bed system is developed.
Fernandes et al. [40]	Theoretical	Closed bed	30 kg	Adsorbent mass, external and internal fins, condensation and evaporation temperature	Heat generated during adsorption for varying parameter.
Deshmukh et al. [41]	Theoretical	Closed bed	350 kg	Adsorbent mass, heat transfer parameter, condensation and evaporation temperature	Heat capacity and maximum temperature lift is optimized.
Lim et al. [30]	Experimental	Closed bed	1.25 kg	Evaporation temperature, water mass in evaporator	Temperature lift, adsorbed water mass
Kant et al. [42]	Theoretical	Closed bed	–	Fin configuration, bed height, fin diameter, fin spacings	Energy discharge, peak power
Ayisi and Fraňa [43]	Experimental and Theoretical	Open bed	800 g	No of cycle	Adsorbed water, temperature lift, specific power, energy released
Wang et al. [44]	Theoretical	Open bed	290 g	Air flow direction, flow rate, charging temperature	Temperature lift
Strong et al. [31]	Experimental	Open bed	50 g	Humidity, particle size, flow rate, charging temperature, insulation	ESD, temperature lift, thermal power, breakthrough behaviour
Present work	Experimental	Open bed	500 g- 2000 g	Humidity, particle size, flow rate, charging temperature, insulation, adsorbent mass	ESD, temperature lift, Storage volume

the previous studies on silica gel-based energy storage system reveals the prominent gap which is listed below:

- Lack of reported data on water adsorption capacity and thermal performance of same silica gel as an energy storage material which is essential to verify any theoretical model and simulate an adsorptive heat storage reactor.
- Inconsistencies in the energy storage density obtained in bench-scale experiments and prototype-scale demonstrations is suspected to originate from the increased amount of adsorbent in the reactor. However, effect of this critical parameter is not examined in laboratory scale experimental studies.
- Existing laboratory scale experimental research performs sensitivity study for a very small adsorbent amount (50 g) which will not be comparable with the prototype energy storage system with bulk scale silica gel in terms of heat and mass transfer.

This study will provide a complete set of experimental data for silica gel as a heat storage material that can serve as the basis for future theoretical and practical designs of sustainable clean energy storage systems. The scope of this work aligns with the “Affordable and Clean Energy” objective of the United Nations Sustainable Development Goals [46]. The major contributions of this work are listed below:

- The water adsorption capacity of a commercially available silica gel, which is the primary controlling factor for designing an adsorptive energy storage system, has been estimated in laboratory experiments.
- An open-cycle test rig has been designed and developed. This system employs a rectangular reactor that can vary the amount of adsorbent in the process, which is a crucial parameter in a bulked-out prototype.
- Heat storage density and temperature lift have been investigated as performance parameters with a range of operating conditions (relative humidity, flow rate, regeneration temperature), and physical parameters (amount of adsorbent and particle diameter) using the same silica gel. The cyclability of silica gel has been checked by repeating the experiment with initial conditions after 15 sets of tests.
- Finally, the critical material storage volume required to meet the space heating demand in a typical UK residence has been estimated.

2. Adsorption kinetic and isotherm

The determining factors in the calculation of the energy storage capacity of a material in an open bed system are its water adsorption capacity and rate of water adsorption. In this study, a climate chamber (KK-105 CH) capable of maintaining a constant temperature (5 °C - 180 °C) and humidity (10 % - 98 %) was operated to measure the water uptake by silica gel. Commercial non-indicating white Type A silica gel (SiO_2) with a bead diameter of 2–5 mm, manufactured by Brownell Ltd., was used for the current study. The manufacturer provided a bulk density of 720 kg/m^3 for this silica gel. The water adsorption measurement test was conducted at 15 °C, 20 °C, and 25 °C while the relative humidity (RH) was varied from 50 % to 90 % at 15 °C, 40 % to 90 % at 20 °C, and 30 % to 90 % at 25 °C at intervals of 10 % in each test. The change in mass of dry silica gel was recorded over 24 h using an electronic balance by taking out the material at 30 min interval for first 6 h and then kept it for overnight to get the equilibrium data. The adsorption process was considered to reach equilibrium when the weight difference was below 5 % in two consecutive 120-min intervals.

The water uptake kinetics of silica gel at 20 °C are shown in Fig. 1, with similar trends observed at the other two temperatures. The last two data points of water uptake at each RH level were taken at a large time gap, which explains the slight increase in water uptake from the usual growth trend. The amount of adsorbed water is higher at increased RH levels because the difference between the water vapor pressure in the air

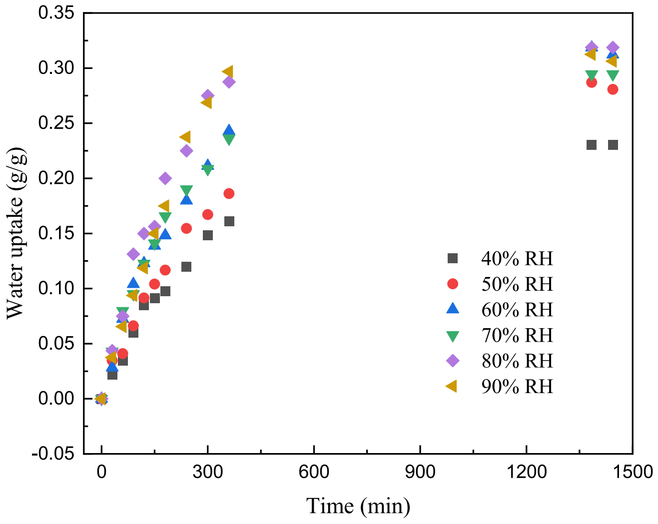

Fig. 1. Experimental water adsorption kinetics for silica gel at 20 °C.

and the equilibrium pressure inside the adsorbent material is elevated at higher RH levels, promoting the effective diffusion of water vapor into the porous adsorbent. However, it is observed that the humidity range of 10 % is too narrow to yield a discernible distinction in the experimental data set for water uptake at 60 %, 70 %, and 80 %, 90 % RH levels.

Water vapor pressure at specific RH can be estimated from following equation

$$P = P_s \times RH \tag{1}$$

where P_s is the saturated vapor pressure and at any given temperature T (°C) can be expressed as [47].

$$P_s = 0.611 * exp(17.27 * T/(237.97 + T)) \tag{2}$$

The amount of adsorbed water is plotted against the water vapor pressure in the air in Fig. 2 to correlate the experimental data into standard isotherms. This enables interpolation of data, required for carrying out theoretical modelling of the adsorption-based energy storage process, at any intermediate points other than the temperature and pressure values at which they have been measured experimentally. The data for the equilibrium adsorption capacity of silica gel for water at three different constant temperatures have been fitted into the Sips isotherm [48] as given in Eq. 3.

$$\frac{C}{C_0} = \frac{(aP)^{1/n}}{1 + (aP)^{1/n}} \times \frac{1}{(1 - P/P_s)^d} \tag{3}$$

In the above equation, C_0, a, n and d are temperature (absolute) dependent constants. Park et al. [49] employed simplified sips isotherm in their investigation, acknowledging the temperature dependency of the associated parameters. The temperature dependent constants from Eq. 3 can be estimated by recording the fitting constants from Sips equation at three different temperature and fitted them in Origin software as temperature dependent functions. and can be expressed as follows.

$$C_0 = 0.0062T^2 - 3.6308T + 533.9 \tag{4}$$

$$a = 1.176 \times 10^{-6} exp(4035.03/T) \tag{5}$$

$$\frac{1}{n} = 1.08 \times 10^{-14} + \frac{740.48}{T} \tag{6}$$

$$d = 0.0016T^2 - 0.9375T + 137.76 \tag{7}$$

The satisfactory fit of the Sips isotherm with temperature-dependent constants to the experimental equilibrium water adsorption capacity data of silica gel is apparent from Fig. 2. The R^2 values for the three fitted curves are 99 %, 98 %, and 99 % for 15 °C, 20 °C, and 25 °C, respectively.

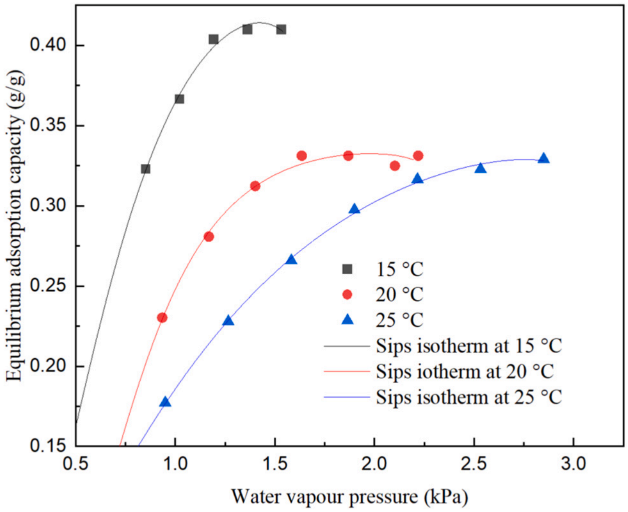

Fig. 2. Equilibrium adsorption capacity data fitted into Sips isotherm.

In the following section, experimental procedure for measurement of energy storage density has been described. Equilibrium adsorption capacity along with energy storage density for the same silica gel will provide a comprehensive data set for characterization of silica gel which is useful for future simulation and prototype design of energy storage systems.

3. Experimental set-up and analysis methods

A laboratory-scale solid sorption-based open energy storage system has been designed and developed to experimentally investigate the adsorption process using silica gel as the adsorbent for water in the system. The main component of this test rig is a rectangular adsorption reactor that can contain a maximum of 4.3 kg of silica gel, and the amount of material in the system can be easily adjusted by adjusting the thickness of filled material. The material regeneration process is performed separately in a drying oven located in the laboratory. This makes the construction and operation of the system simple, without affecting the objective of estimating the energy storage capacity of the material at different charging temperatures. This system can conduct the adsorption process at different inlet humidity levels, air flow rates, material amounts, regeneration temperatures, adsorbent particle sizes, and insulation amounts on the reactor. It can also test the cyclability of the adsorbent material. The system records inlet and outlet temperatures and humidity and air flow rate, which are used to calculate key performance variables such as energy storage density and temperature lift. Besides of using calculation based on humidity changes, the amount of adsorbed water is also measured by weighing the reactor after every test, which helps to analyse the effect of the above-mentioned variable parameters. These experiments observe the effect of all the parameters that can possibly affect a practical open bed energy storage process, making this study an important contribution to this area of research. The methodology for the experimental evaluation of the silica gel-based energy storage system has been presented in Fig. 3.

3.1. *Test rig*

The schematic of the open bed thermal storage process has been illustrated in Fig. 4. The concept involves passing cold and humid air through an adsorption column to obtain dry and hot air at the outlet after the silica gel adsorbs residual water content from the air, thereby releasing the stored thermal energy from the material. Temperature and relative humidity at the inlet and outlet have been recorded, and the air flow rate at the outlet has been measured to estimate the amount of air passing through the system. For the present system, a rectangular duct with a perforated metal sheet attached to one end for holding the adsorbent material has been designed as the reactor. The reactor is held in place by two square-to-round ducts, which are sealed with a rubber-like foam strip and tightened by nuts and bolts. Adhesive foam insulation is wrapped around the reactor and the reactor holder duct to limit heat loss from the system. The insulation on the outside duct is covered with reflective aluminium foil to create a radiant barrier.

The photograph of the physical experimental setup is presented in Fig. 5. The first component of the system is a humidifier, which uses a water pump from a bucket of water to increase the humidity level in the inlet air stream. A controlling valve is attached to the water pump to adjust the amount of water and consequently, the moisture content in the air stream. Radom-shape plastic rings are used in the packed column to enhance the contact between air and sprayed water. A fan with a regulator has been employed to propel the moist air stream to the reactor.

The second component of the test rig is the reactor, which contains silica gel. A rectangular duct with dimensions of 200 × 200 × 150 mm

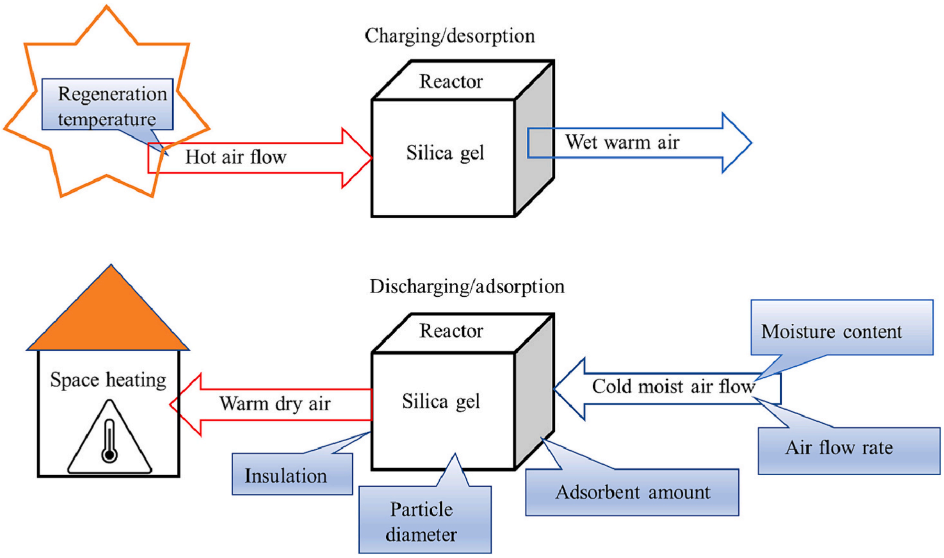

Fig. 3. Layout of the experimental parametric variation performed in this study.

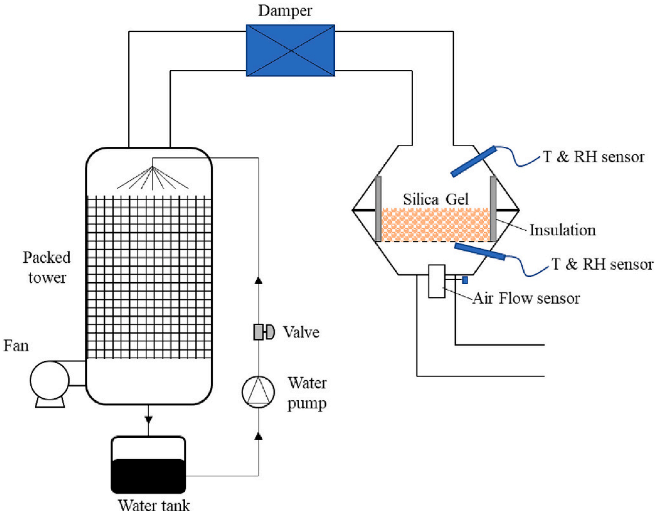

Fig. 4. Schematic of the concept of the open bed heat storage process.

has been utilized as the reactor. A stainless-steel mesh sheet with a 1 mm hole diameter is attached to the outlet side of the duct to hold the silica gel and allow the air to pass through the material. To limit heat loss, foam insulation strips have been affixed to the outer surface of the adsorbent container duct.

The reactor was initially filled with 1000 g of silica gel when the other operating parameters were altered. Suitable sensors were installed in the system to record temperature, humidity, and flow rate of air. K-type thermocouples were installed at the immediate inlet and outlet of the reactor to measure the air temperature. Two combined relative humidity and temperature transmitters, HX15-D from Omega (UK), which have a measuring capacity range from 3 % to 95 % RH with a ± 2 % RH uncertainty, were mounted very close to the inlet and outlet of the reactor. The volumetric flow rate at the outlet was measured by an air flow meter, AWM720P1 from Honeywell, which works in a temperature range of −25 °C to 85 °C with an accuracy of 0.5 % and is capable of measuring a maximum of 200 SLPM of flow. To estimate the amount of adsorbed water, the mass change of the silica gel after each adsorption test was measured by an electronic weighing scale CKE 6K0.02 from Kern with maximum weighing capacity of 6000 g and accuracy of 0.02 g. DataTaker DT85 was used to collect data every 30 s.

3.2. *Experimental procedure*

The breakthrough adsorption tests comprise of three stages. The initial step involved the preparation of the silica gel prior to each experiment. Silica gel particles with a diameter of 4–5 mm were sieved and weighed to obtain 1000 g for drying. This silica gel was dried in an oven for eight hours at 120 °C and then left to cool in an airtight glass container overnight before loading it into the reactor. The second stage of the experiment involved setting up the desired operating conditions for adsorption to occur. In this study, the air flow rate and relative humidity were first varied to determine the optimum operating conditions. Heat discharge through adsorption experiments was performed with air flow rates of 66 L/min, 100 L/min, 133 L/min, and 166 L/min at humidity levels of 40 %, 60 %, and 80 %. The water pump with controlling valve to increase the moisture content and the fan with regulator to drive the moist air to the reactor were adjusted to ensure that the experimental conditions were within the predetermined ranges. The third stage was to allow the adsorption of water by silica gel to occur in a controlled environment. The inlet air duct damper was opened, and air with the desired relative humidity passes through the adsorbent material at a regulated flow rate. When the water moisture in the air encounters silica gel, adsorption occurs, releasing the adsorption heat and generating hot air at the outlet of the reactor. The outlet temperature begins to fall off after reaching a peak and returns to room temperature, indicating the completion of the discharging process. The entire process can be represented by the breakthrough curves for temperature and concentration, which are obtained by measuring and recording temperature and relative humidity at the entry side and the exit of the reactor throughout the experiment. All three stages were repeated to conduct a series of experiments at different operating conditions to identify the optimum relative humidity level and air flow rate for the process. At that condition, other operating conditions, such as regeneration temperature, amount of silica gel material and particle diameter, were altered to observe their effect on the heat discharge process. The main performance parameters are identified as maximum temperature lift and energy storage density, which were calculated and compared for every parameter.

3.3. *Analysis method*

The temperature and relative humidity profiles at the inlet and outlet of the reactor were monitored for all experimental conditions. The temperature lift was calculated by determining the difference between

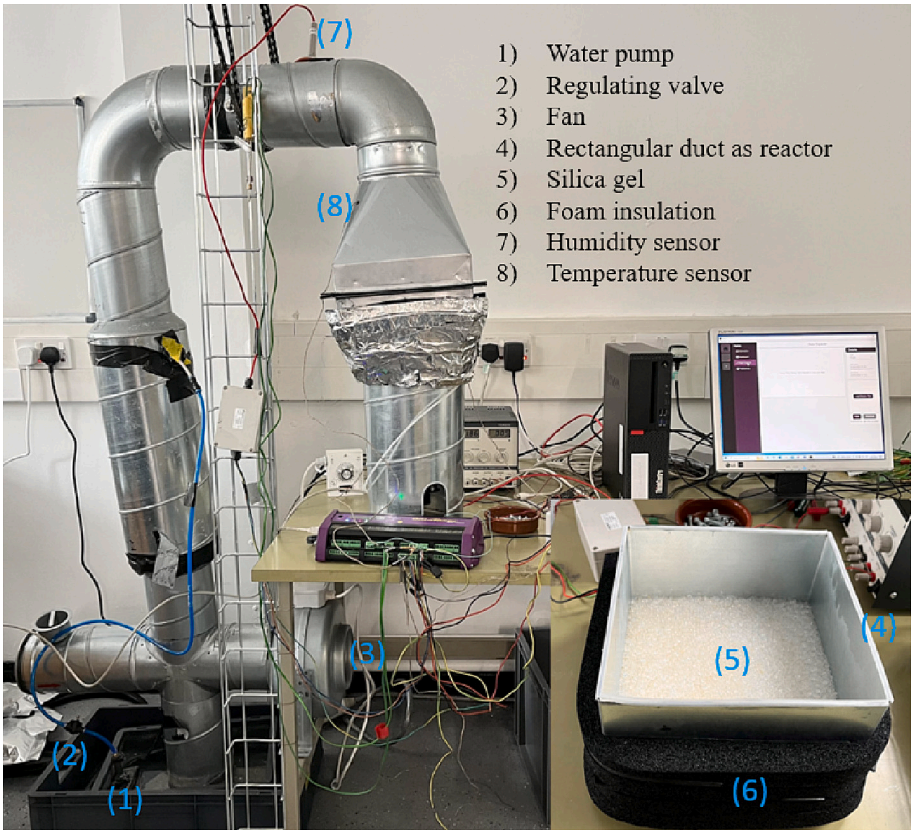

Fig. 5. Photograph of actual experimental test rig.

the maximum outlet temperature and the inlet temperature. Stored energy in silica gel during charging is calculated from discharged energy during adsorption and was expressed as [31].

$$Q_{ads} = \int_0^t \dot{m}_f C_{p,air}(T_{out} - T_{in})dt \tag{8}$$

where $\dot{m}_f$ is the air flow rate, $C_{p,air}$ denotes specific heat capacity of moist air and t defines the total time to complete the process.

The energy storage density (ESD) of the adsorbent was determined using the following equation:

$$ESD = \frac{Q_{ads}}{M_{ads}} \tag{9}$$

M_{ads} is the dry mass of silica gel utilized for the process.

The energy storage density of the adsorbent and temperature lift during the adsorption process were compared first, while varying the relative humidity and flow rate in a mutually exclusive manner to determine the optimal conditions. At this optimal air flow rate and relative humidity, the effect of another critical operating parameter, the regeneration temperature, was observed. Subsequently, the impact of physical parameters such as particle diameter, mass of adsorbent, and amount of insulation on the released energy density and temperature lift were investigated at the best operating conditions. Following these sets of experiments, the temperature and concentration profile were re-examined and compared with the initially obtained profile at the optimal operating and physical conditions to evaluate the cyclability of the used silica gel. Table 2 provides a list of the test cases for variable parameters and the values of the fixed conditions for each instance.

4. Results and discussion

In this segment, the impact of various operating and physical conditions (Table 2) on the energy storage density and resulting temperature rise for this silica gel based open bed heat storage system have been assessed. Primarily, a representative concentration and temperature profile during adsorption process has been presented for a specific scenario. Fig. 6 exemplifies the concentration and temperature profile as a function of time for an air flow rate of 100 L/min and a supplied relative humidity of 80 % at the inlet. At the beginning of the adsorption process, the outlet air temperature starts to increase almost immediately, and the outlet relative humidity is zero straightforwardly, indicating the occurrence of significant adsorption. In the current system and condition, the outlet relative humidity takes two hours to reach 2.5 % of the inlet concentration. At this point, most of the adsorption sites in the fully regenerated silica gel are vacant, and the adsorbate (water vapor in the air) gets adsorbed instead of passing through the outlet of the reactor. This time is known as the breakthrough time, and an extended breakthrough time indicates a higher adsorption capacity of the adsorbent. The outlet temperature shoots up as soon as the adsorption of water vapor occurs in the silica gel. It reaches its maximum within the breakthrough time and starts to decrease due to heat transfer to the reactor wall and the ambient. Once the adsorption process proceeds beyond the breakthrough time, the relative humidity in the outlet air begins to increase slowly, and ideally, it should reach the supplied relative humidity level when no vacant adsorption sites are available in the adsorbent. However, a deviation of 13 % between the relative humidity at the inlet and outlet of the reactor is observed. This is majorly caused by system pressure drop due to kinetic energy loss originating from different sized flow channels through piping and reactor [45] and due to friction factor when air is flowing through the packed adsorbent bed [50]. The time required for the silica gel to become saturated with water is known as the saturation time, and the adsorption process is stopped after this time. At saturation time, the outlet temperature decreases to the inlet temperature, which indicates that no further thermal energy will be released. For the current system and conditions, the

Table 2
Test cases for each parametric variation.

Test case	Variable parameter	Variation	Fixed parameter	Values
Condition 1	Relative humidity	40 %, 60 %, 80 %	Air flow rate Regeneration temperature Insulation Particle diameter Amount of silica gel	66 L/min 120 °C Reactor and reactor holder 4–5 mm 1000 g
Condition 2	Relative humidity	40 %, 60 %, 80 %	Air flow rate Regeneration temperature Insulation Particle diameter Amount of silica gel	100 L/min 120 °C Reactor and reactor holder 4–5 mm 1000 g
Condition 3	Relative humidity	40 %, 60 %, 80 %	Air flow rate Regeneration temperature Insulation Particle diameter Amount of silica gel	133 L/min 120 °C Reactor and reactor holder 4–5 mm 1000 g
Condition 4	Relative humidity	40 %, 60 %, 80 %	Air flow rate Regeneration temperature Insulation Particle diameter Amount of silica gel	166 L/min 120 °C Reactor and reactor holder 4–5 mm 1000 g
Condition 5	Regeneration temperature	60 °C, 90 °C, 120 °C	Relative humidity Air flow rate Insulation Particle diameter Amount of silica gel	80 % 100 L/min Reactor and reactor holder 4–5 mm 1000 g
Condition 6	Insulation	Only over reactor	Relative humidity Air flow rate Regeneration temperature Particle diameter Amount of silica gel	80 % 100 L/min 120 °C 4–5 mm 1000 g
Condition 7	Particle diameter	2–3 mm	Relative humidity Air flow rate Regeneration temperature Insulation Amount of silica gel	80 % 100 L/min 120 °C Reactor and reactor holder 1000 g
Condition 8	Amount of silica gel	500 g, 1 kg, 2 kg	Relative humidity Air flow rate Regeneration temperature Insulation Particle diameter	80 % 100 L/min 120 °C Reactor and reactor holder 4–5 mm

process takes 15 h and 25 min to complete. A similar trend in temperature and concentration profiles is recognized in all the experiments.

In the next sub-sections, sensitivity analysis for various conditions (relative humidity, flow rate, regeneration temperature, amount of insulation, particle diameter, amount of adsorber in the reactor) have been performed and discussed.

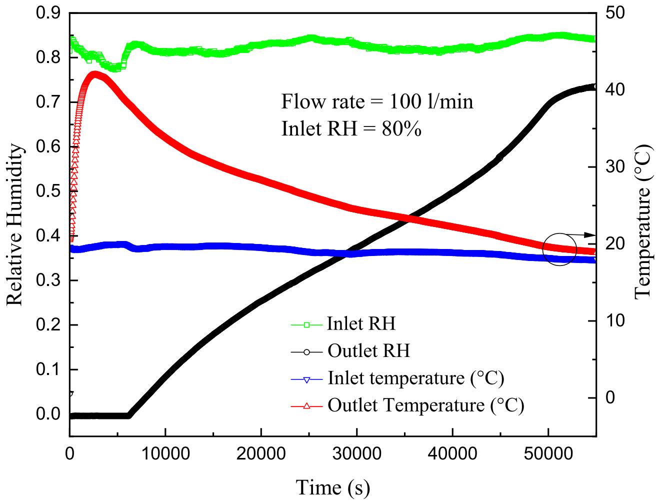

Fig. 6. Temperature and relative humidity profile at inlet and outlet of the reactor with air flow rate 100 L/min and supplied relative humidity 80 %.

4.1. Effect of relative humidity and flow rate

The impact of relative humidity on the temperature lift and energy storage capacity of used silica gel was investigated at different relative humidity level of 40 %, 60 %, and 80 % using a constant air flow rate. Four different air flow rates of 66 L/min, 100 L/min, 133 L/min, and 166 L/min were chosen for the study. Since the current experiment uses ambient air as the carrier fluid, the inlet air temperature varies for each set of experiments, making temperature lift a significant performance parameter for comparing the data, rather than the outlet temperature profile.

Fig. 7 shows the effect of three different relative humidity levels at four constant air flow rates on temperature lift. At all flow rates, temperature lift is higher with increased humidity levels because the inlet air holds more water vapor, creating a larger pressure difference to drive the adsorption process more efficiently, and accordingly increasing the water adsorption capacity of silica gel. More water adsorption by silica gel accelerates the exothermic characteristics of the process and in turn enhances the temperature of air at the exit of the reactor. Results depicted in Fig. 7 show that the maximum temperature lift of 22.4 °C has

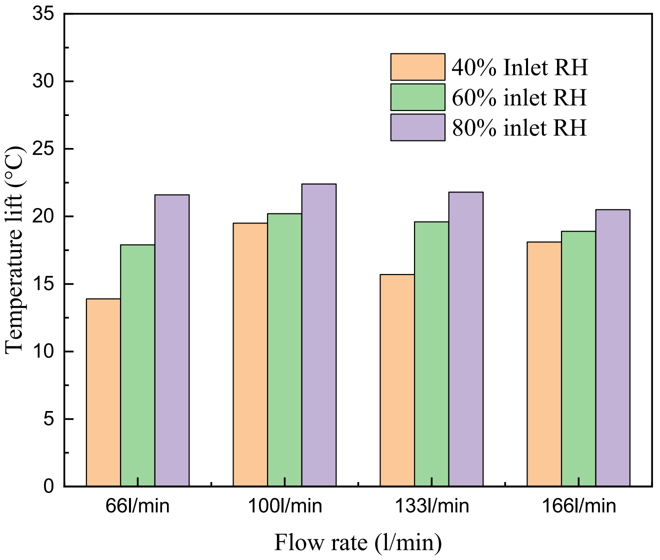

Fig. 7. Effect of increasing relative humidity on temperature lift during adsorption, condition 1–4.

been observed at 80 % RH and 100 L/min. Similar to the data for maximum temperature lift, energy storage density also exhibits a positive trend with increasing relative humidity in the feed air as shown in Fig. 8. However, the percentage of increment in temperature lift and energy storage density differs with higher RH levels. At a 100 L/min air flow rate, the increase of temperature lift is 15 %, while ESD is improved by 33 % when RH is elevated from 40 % to 80 %. This is because the maximum temperature lift is dependent on the rate of adsorption of water by silica gel, whereas the energy storage density of silica gel is mainly controlled by the amount of adsorbed water in the whole duration of the process. Therefore, the duration of the entire reaction has a prominent role in determining the total energy storage density of the material. As seen in Fig. 6, the outlet temperature profile will have a lift from the inlet temperature profile for a very long time, generating the requisite ESD in the process. The amount of water adsorbed is measured for each process by weighing up the silica gel before and after the process and mapped in Fig. 9. Adsorbed water is maximum at 80 % RH for each air velocity, which supports the findings in Fig. 8. The highest energy storage density of 925 kJ/kg has been obtained at 80 % RH and 100 L/min air flow rate. In summary, an increase in the RH level at the inlet air is favourable for both the maximum temperature lift and energy storage density and should be positively adjusted according to the requirement for a specific application.

Another noteworthy observation from Figs. 7 and 8 is that air flow rate significantly affects both performance parameters. It can be observed that there is no consistent trend in the change of maximum temperature lift and energy storage density with the increase in flow rate from 66 L/min to 166 L/min. The maximum temperature lift and ESD are highest at 100 L/min. At 40 % humidity level, increasing air flow rate beyond 100 L/min does not have a significant impact on maximum temperature lift and energy storage density. At the other two humidity levels, both performance parameters slightly decrease as flow rate is increased from 100 L/min. The most prominent effect can be seen at 80 % RH. An increase in air flow rate results in water vapor reaching the silica gel more quickly, leading to increased mass transfer kinetics and heat transfer rate. On the one hand, faster kinetics of mass transfer enhances water vapor transport and diffusion into the pores of silica gel, thus raising the temperature at the outlet. Conversely, higher air velocity effectively decreases the interaction time between adsorbate and adsorbent, which has a negative effect on energy storage density [31]. This fact is supported by Fig. 10, which compares the outlet relative humidity profile for four different flow rates at 80 % RH. It shows that the outlet relative humidity reaches 70 % humidity in less than 8 h at an air flow rate of 166 L/min, whereas it takes more than 17 h to reach the same level at 66 L/min. However, as a result of faster mass transfer kinetics, the pressure drop at the outlet is greater at an air flow rate of 166 L/min compared to 66 L/min, which favours the generation of higher outlet temperature.

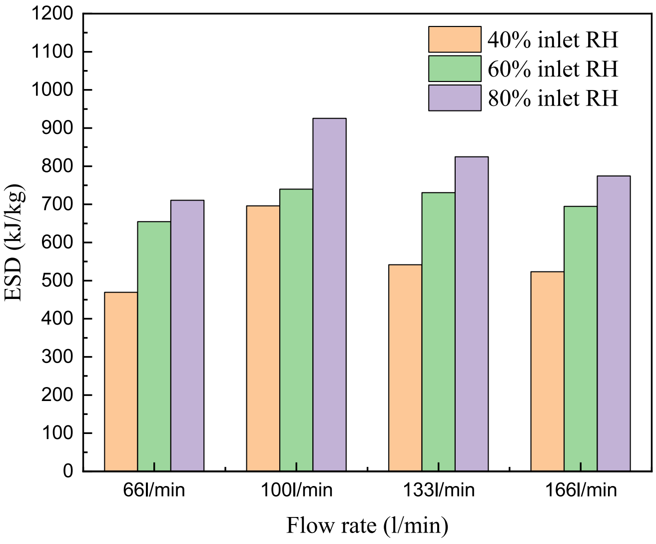

Fig. 8. Effect of increasing relative humidity on energy density, condition 1–4.

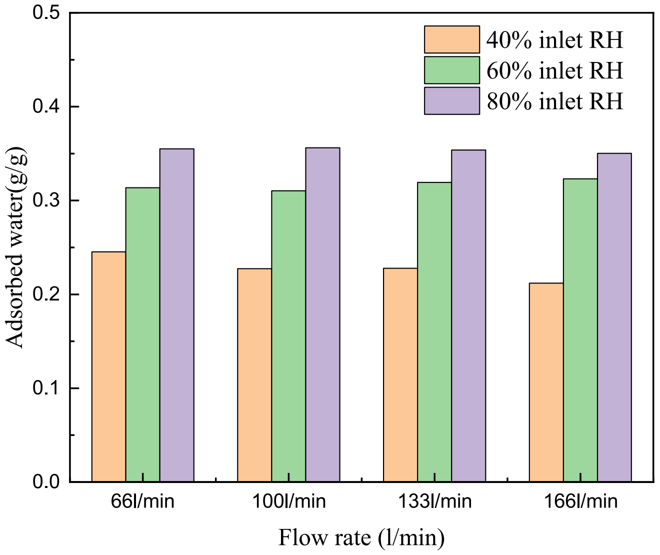

Fig. 9. Amount of adsorbed water by silica gel at different humidity level, condition 1–4.

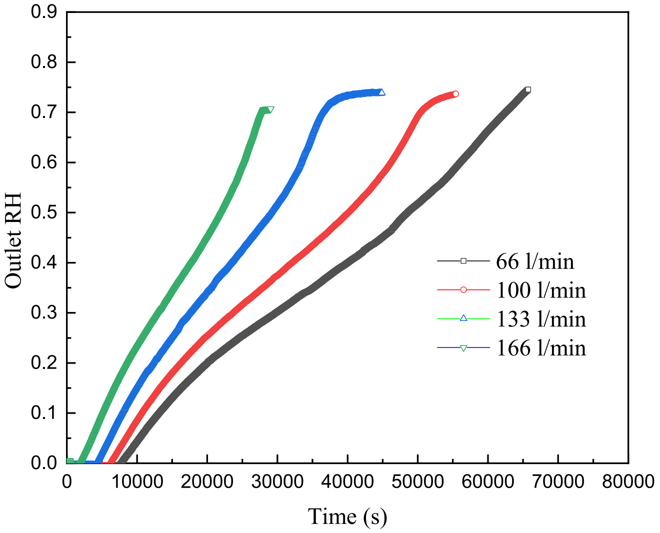

Fig. 10. Outlet relative humidity profile for different air flow rate at 80 % RH.

Furthermore, a faster heat transfer rate also means more heat loss, which lowers the energy storage capacity of the adsorbent. Thus, the contradictory effect of increasing air flow velocity on the heat storage process demands finding an optimum value for any system, which is 100 L/min for the current experiment.

4.2. Effect of regeneration temperature

Based on results from Condition 1–4, 80 % RH level and 100 L/min air flow rate were used to analyse the impact of other variables on the system's performance. One critical parameter that determines the feasibility of a particular adsorbent for a renewable energy source is its regeneration temperature. Previous literature has extensively studied this property of silica gel and found it to be 120 °C. However, it is essential to investigate the effect of dehydrating silica gel at a lower temperature, which can be practically achieved using a solar collector. For the present experimental study, silica gel was regenerated at 90 °C and 60 °C and used for water adsorption to estimate the released energy for both cases. The computed energy storage capacity and maximum temperature lift for all three cases are depicted in Fig. 11. When desiccated at a lower temperature, the silica gel cannot be fully regenerated, leaving water vapor attached to some of the material's pores. Thereafter this poorly regenerated adsorbent has fewer available sites to capture water vapor when used for adsorption, resulting in a reduced temperature lift and ESD from the system. As shown in Fig. 11, the ESD is depleted by 38 %, while the maximum temperature lift is reduced by 24 % when regenerated at 60 °C compared to the case of 120 °C.

4.3. Effect of amount of insulation

The impact of insulation on the outlet temperature profile was investigated by removing the additional insulation around the reactor holder duct and keeping only the primary insulation around the reactor, as shown in Fig. 12. Since the insulation over the reactor or reactor holder can only affect the heat transport to the exterior, the main impact of this variation is only on the exit air temperature. A comparison of the outlet temperature profiles in Fig. 12 clearly shows a significant increase in heat loss to the surroundings after reaching the maximum temperature. This leads to a reduction in the time required to reach the inlet temperature after completion of adsorption, thereby negatively affecting the ESD of the system. When the insulation over the reactor holder is eliminated, the ESD is reduced from 925 kJ/kg to 486 kJ/kg.

4.4. Effect of particle diameter

The silica gel utilized in the current tests has been commercially sourced and comes in a bead size of 2–5 mm diameter. A sieve with a diameter of 3 × 3 mm is employed to separate particles of 2–3 mm and 4–5 mm diameter. In the previous set of experiments described in this article, silica gel with a 4–5 mm diameter is utilized. The effect of a smaller particle diameter on the energy storage capacity of silica gel and the maximum temperature lift is presented in Fig. 13. Although there is no significant impact of the reduced particle diameter on the maximum temperature lift, the ESD slightly increases (by 11 %) with the smaller particle size. The size of the beads comprising the adsorbent material plays a crucial role in determining the efficiency of mass transfer kinetics and heat transfer properties within a packed reactor. The overall mass transfer kinetics within the bed are influenced by both inter-particle and intra-particle mass transfer resistance [51]. Reducing the diameter of the particles promotes improved intra-particle mass transfer, resulting in an accelerated adsorption rate. Conversely, smaller particles with narrower porous channels increase inter-particle mass transfer resistance, leading to a significant pressure gradient throughout the reactor. The opposite effect occurs with larger particles. The heat transfer process within the adsorbent bed involves both conductive and convective heat transfer. When smaller particles are used, the contact thermal resistance, which is part of the conduction process, decreases [52]. However, the convective heat transfer coefficient, which depends on the superficial fluid velocity, decreases for the same particle size variation. Since achieving maximum heat storage capacity requires increased mass transfer and reduced heat transfer rates, it is more reasonable to propose that there may be an optimal particle diameter that is most suitable for the given application [53]. The bead diameter of the adsorbent mainly influences the pressure drop and mass transfer kinetics in an adsorption process. According to Ergun's equation [54], a decrease in particle size causes a higher pressure drop between the inlet and outlet of a reactor, which is favourable for more adsorption to occur. In addition, water vapor in the airflow can easily access the pores of silica gel when the reactor is packed with smaller particles, leading to an increased mass

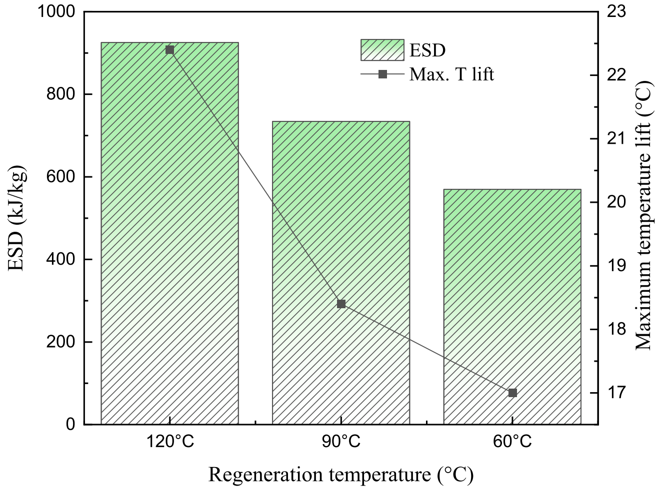

Fig. 11. ESD and maximum temperature lift for different regeneration temperature, condition 5.

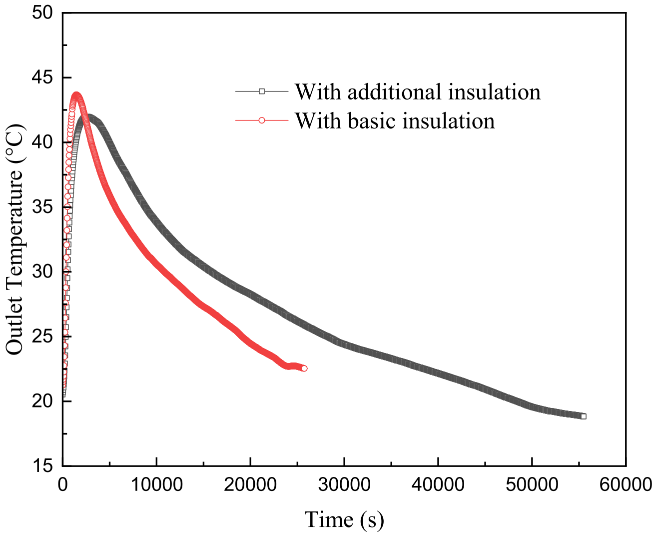

Fig. 12. Effect of using additional insulation over reactor holder on outlet temperature profile, condition 6.

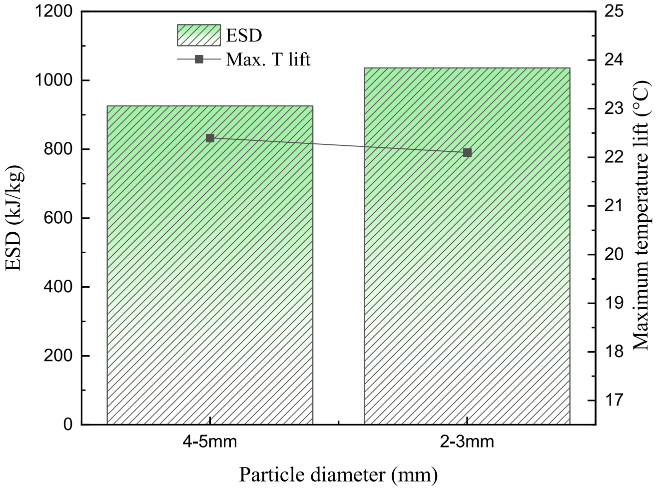

Fig. 13. Effect of particle diameter on ESD and maximum temperature lift, condition 7.

transfer coefficient value. However, increasing the mass transfer rate can negatively impact the energy storage capacity in terms of the time required to complete the process. Therefore, it is more reasonable to suggest that there may be an optimum value of particle diameter that is best suitable for the application. It is worth noting that the mesh size of the particle was not altered when a smaller particle was used. Due to the non-availability of silica gel with a particle diameter smaller than 2 mm with the same mesh size in the laboratory, the previous statement was not experimentally established.

4.5. *Effect of amount of adsorbent in the reactor*

In the process of scaling up the design of the energy storage process from the laboratory to the prototype level, the amount of adsorbent used must be increased significantly. Therefore, it is crucial to investigate the effect of changing the amount of adsorbent in the reactor. However, the authors could not find any research that has experimentally investigated this aspect. Experiments were conducted using 500 g, 1000 g, and 2000 g of material to observe the effect on energy storage density and maximum temperature lift. Fig. 14 shows a 57 % increase in energy storage capacity when the amount of material is decreased from 2 kg to 500 g. At the same time, the figure indicates a 31 % increase in maximum temperature lift when 2 kg of silica gel is used compared to 500 g. When more adsorbent is used in the current system, the direct effect of more water adsorption contributes to a higher temperature lift. However, the same change in the amount of adsorbent also increases the thickness of the adsorbent layer, which creates resistance to water vapor transport to all the adsorbent particles. This analysis suggests that the prototype design for practical application requires a number of water vapor transport systems inside the reactor to create an optimum adsorbent thickness around the vapor transport system and counteract the adverse effect of increasing the amount of adsorbent in the reactor.

5. Cyclability of silica gel

Finally, after conducting all the experiments described in this study, the cyclic performance of the silica gel was evaluated in terms of outlet relative humidity and temperature profile since the same silica gel was employed for all the parameter variations. The cyclic performance of the silica gel was tested at the 15th cycle. The outlet temperature and relative humidity profiles for the first and fifteenth tests are depicted in Fig. 15. It can be observed that there is negligible variation in both profiles, which only impacts the energy storage capacity by a mere 0.8 %. This result indicates that the utilized silica gel is appropriate for recycling in a long-term seasonal heat storage application.

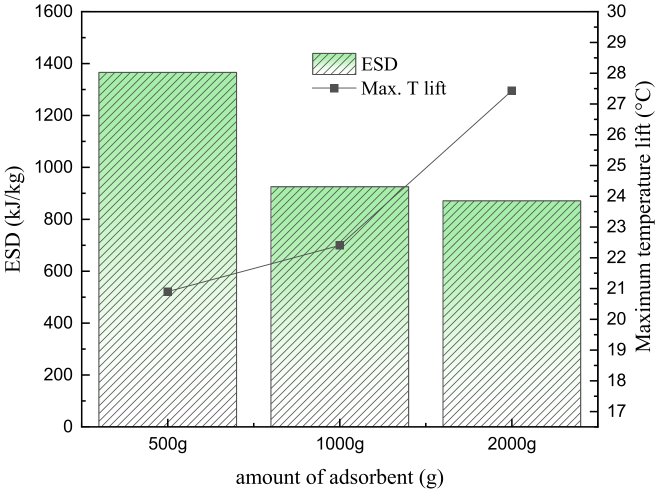

Fig. 14. Effect of amount of adsorbent in the reactor on ESD and maximum temperature lift, condition 8.

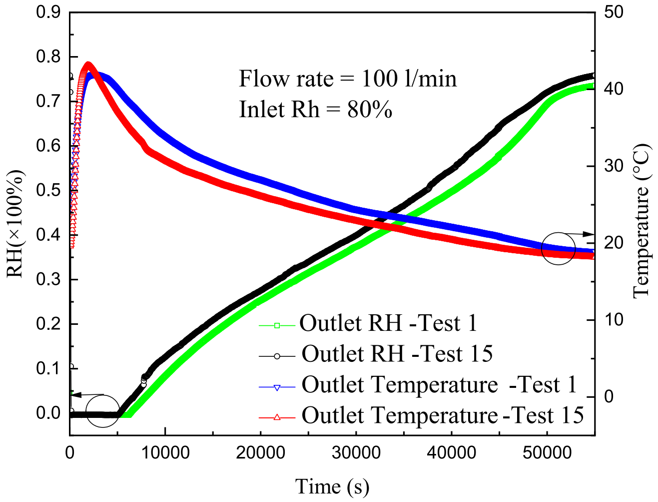

Fig. 15. Comparison of outlet pressure and temperature profile obtained from test 1 and test 15 when supplied RH: 80 % and air flow rate: 100 L/min.

6. Storage volume required for practical application

Table 3 presents the selected parametric conditions to achieve the highest energy storage density, which amounts to 273 kWh/m^3 for the current open bed silica gel-based system. A crucial design parameter to consider is the critical storage volume required to develop an energy storage prototype that can meet the demand for real-world space heating. Ma et al. [43] analysed weather data from various cities in the UK and found that the average temperature in Newcastle during winter months (October to March) is 6 °C. They utilized the following equation to estimate the energy demand for domestic space heating in kWh

$$Q_{sh} = \overline{UA}(T_{room} - T_{amb})/1000 \tag{10}$$

The above equation assumes an overall heat loss coefficient $(\overline{UA})$ of 150 W/K for a typical semi-detached building, which represents the average value within a range of 50–250 W/K depending on building and wind flow characteristics. The average indoor temperature required for comfortable living is reported to be 21 °C in the same study [55]. According to Eq. 10, the total space heating demand during the October to March period in Newcastle is estimated to be 9827 kWh. Considering, all the heat discharged during adsorption can be utilized for space heating, a storage volume of 36 m^3 of adsorbent is required to meet the demand.

Fig. 16 illustrates a comparison between the achieved energy storage density and the material storage volume required to fulfil the space heating demand for a typical residence in Newcastle using a silica gel based adsorption energy storage system, based on previous studies. It should be noted that the energy storage densities estimated in these studies were based on different operating and physical parameters than those of the present study, underscoring the importance of an experimental parametric study for the development of an efficient energy storage system.

Table 3
Best case scenario obtained from parametric evaluation.

Parameters	Values
Relative Humidity	80 %
Air flow rate	100 L/min
Regeneration temperature	120 °C
Insulation	Additional insulation over reactor holder
Particle diameter	4–5 mm
Amount of adsorbent	500 g

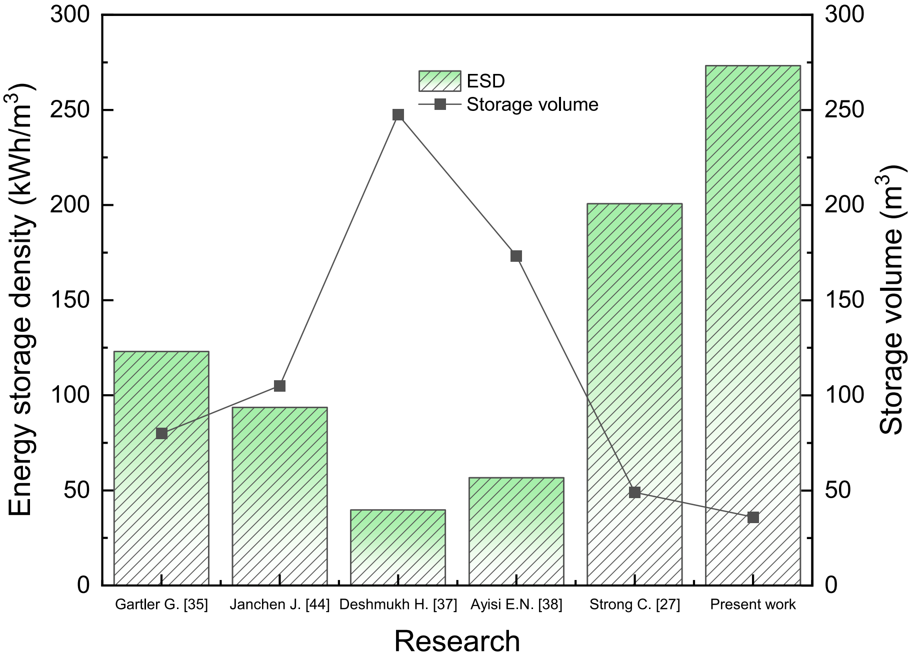

Fig. 16. Comparison of volumetric energy storage density and required storage volume in present work with the previous studies.

7. Conclusions

The objective of this study was to assess the efficacy of a commercial silica gel as an energy storage material in a bulk scale, open bed, adsorption-based system under varying physical and operational conditions. The energy storage density and temperature lift of the material were selected as performance parameters. The major conclusions drawn from the parametric study are as follows:

- The adsorption heat released per unit mass of silica gel increases from 696 kJ to 925 kJ when RH is increased from 40 % to 80 %, while the inlet air flow rate is kept constant. The maximum temperature lift is improved from 17 °C to 22 °C with the same change in RH. The main reason for these positive findings is the enhanced amount of adsorbed water due to the increase in relative humidity.
- In addition to changing the RH of incoming air, adjusting the air flow rate is necessary to promote ESD and temperature lift. The effect of the inlet air flow rate on the system's performance resulted in a trade-off between an elevated driving force and a reduced time required for the completion of the adsorption process. This analysis suggests that an optimum air flow rate must be considered when designing this energy storage technology. An air flow rate of 100 L/min was found to be the optimum condition in the current experimental research.
- Although decreasing the dehydration temperature from 120 °C to 60 °C decreased the ESD and maximum temperature lifts by approximately 38 % and 24 %, respectively, silica gel is still a better choice for solar energy applications.
- The use of additional insulation over the reactor holder, in addition to the basic insulation only around the reactor, was found to be beneficial in terms of restricting heat loss to the surroundings and consequently improving the energy storage capacity by 90 %. This result implies that limiting heat loss to the exterior is significant when designing this type of heat storage system.
- A decrease in particle size by 1–2 mm has a small effect (11 %) on the energy storage density, while the maximum temperature lift remains unaffected.
- When the amount of silica gel in the reactor is increased from 500 g to 2 kg, the ESD deteriorates by 38 %, while the maximum temperature lift improves by 31 %. Enhanced resistance to mass transfer causes the decrease in ESD. This indicates that a significant amount of research should be directed toward the advancement of the water vapor transport system when designing a prototype of an adsorption-based thermal energy storage system.
- The repeatability tests in this study recommend that there is a slight (0.8 %) performance deterioration from the first test to the fifteenth test, suggesting that this commercial silica gel is suitable for recycling in a long-term seasonal heat storage application.
- Finally, an estimation has been made for the storage volume of material required to fulfil the space heating requirements of a typical UK household, which is deemed to be 36 m^3. This value represents a noteworthy improvement over the findings of prior research.

Based on the findings and conclusions of this study, future experimental research should explore the solutions to enhance the mass transfer with advancement of vapor transport system in the reactor to maximize the energy storage density and mitigate the negative effect of increased mass in the reactor. Another prospective approach of future work involves the utilization of innovative materials characterized by lower heat transfer resistance to expedite heat discharge. Subsequent simulation efforts may leverage the insights gained from this research concerning the adsorption capacity and energy storage density of silica gel. These simulations can be employed to conduct techno-economic analyses, evaluating the cost-effectiveness of the proposed heat storage system. The collective findings of the present study and the proposed future investigation could contribute to the practical implementation of this technology.

CRediT authorship contribution statement

Susmita Koley: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Huashan Bao:** Funding acquisition, Project administration. **Anthony Paul Roskilly:** Funding acquisition, Project administration, Resources. **Zhiwei Ma:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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