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Analysis of thermochemical storage materials for waste heat recovery from data centres

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Abstract:

ThermoChemical Energy Storage (TCES) represents a promising solution for the recovery and reuse of low-grade waste heat, particularly in applications such as data centres, where large amounts of thermal energy are dissipated at relatively low temperatures. In this work, the performance of a silica gel-based TCES system is investigated under operating conditions representative of seasonal heat recovery. A dynamic numerical model was developed in MATLAB to simulate the coupled heat and mass transfer processes occurring in an open-bed reactor during both adsorption (discharging) and desorption (charging) phases. The model was validated against experimental data obtained from a laboratory-scale test bench. The validated model was then used to analyse system performance under representative winter and summer operating conditions, for a silica gel sample of height 0.08 m and diameter 0.076 m. During adsorption (winter), with inlet air at 10.0 °C and 80.0 % relative humidity, the system provides a temperature lift of up to 14.4 °C; the results show that most of the useful thermal effect is concentrated in the initial phase, while extending the operating time leads to limited additional benefit despite residual adsorption capacity. During regeneration, with inlet air at 65.0 °C and 10.0 % relative humidity, the material is almost completely regenerated; this phase is characterised by a strong initial thermal demand. Overall, the results demonstrate the feasibility of using silica gel-based TCES systems for low-temperature waste heat recovery and highlight the importance of optimising operating conditions and cycle duration to maximise system efficiency.

Keywords:

Thermochemical Energy Storage; Sorption; Silica Gel; Waste Heat Recovery; Dynamic Heat&Mass Transfer

1 Introduction

1.1 Waste heat from data centres and the need for thermal storage

The ongoing energy transition is increasingly influencing multiple sectors, particularly in engineering design, where the implementation of circular approaches is becoming essential rather than optional. One of the key objectives is the minimisation of waste in both material and energy production processes, together with the integration of efficient recovery systems capable of reducing environmental impact **[1]**. In this context, data centres represent a rapidly growing source of energy consumption and associated waste heat. In 2022, the global electricity consumption of data centres was estimated between 240 and 340 TWh **[2]**, and it is expected to approximately double by 2030 **[3, 4]**. The fundamental characteristic of data centres is the conversion of electrical energy into heat, with a ratio of 1:1: the combination of increasing loads, continuous 24/7 operation, and high equipment concentration leads to a substantial rise in cooling demand. The increasing cooling demand results not only in a higher overall electrical load, but also in greater availability of low-temperature waste heat. Heat dissipated by the cooling system is a thermal resource that is currently underutilised. However, a major limitation in exploiting this resource is its relatively low temperature level, typically in the range of 30–60 °C, and the temporal mismatch between heat availability and demand. These aspects make the direct use of waste heat challenging in some contexts, and underline the need for efficient thermal energy storage solutions capable of decoupling heat production and utilisation.

1.2 Thermochemical energy storage for low-temperature applications

Among the available thermal energy storage technologies, thermochemical energy storage (TCES) systems are particularly promising for low-temperature applications. TCES relies on reversible sorption or chemical reactions, allowing significantly higher energy densities and negligible heat losses during storage periods **[5]**. In particular, adsorption/desorption-based systems (sorption systems), typically involving a solid sorbent and a gaseous working fluid, have attracted considerable attention.

The silica gel–water pair is one of the most widely studied combinations due to its stability, availability, and favourable adsorption characteristics **[6–9]**. In these systems, energy is released and stored through the adsorption and desorption of water vapour, which are inherently coupled heat and mass transfer processes. The performance of silica gel-based systems strongly depends on operating conditions, especially regeneration temperature and ambient humidity.

While optimal regeneration can be achieved at temperatures around 100–120 °C, lower regeneration temperatures (e.g., 60 °C) may significantly reduce the achievable energy density **[10]**. This aspect is particularly relevant for applications involving low-grade waste heat, where the available temperature levels are limited. To address these limitations, research has also explored advanced materials, such as composites based on the Salt-In-Porous-Matrix (SIM) concept, where hygroscopic salts are embedded into porous structures to enhance adsorption capacity **[11–13]**. However, even when using conventional materials such as silica gel, the optimisation of operating conditions and reactor configurations remains a key factor in improving system performance, particularly in open-bed systems where air directly flows through the material.

1.3 Aim and novelty of the work

Given this premise, the present study is carried out in the context of the European Union Horizon project THUNDER (THermochemical storage Utilization eNabling Data center seasonal Energy Recovery) **[14]**, which aims at recovering waste heat from data centres and storing it in thermochemical systems for later use, for instance in combination with heat pumps. The study focuses on the analysis of a silica gel-based thermochemical storage system operating in an open configuration, where humid or dry air flows through a packed bed of material. A laboratory-scale test bench was developed at the Thermo Lab of the University of Florence to perform experimental investigations on thermochemical materials and to provide reliable data for model validation **[15]**. A dynamic numerical model was developed in MATLAB to simulate the coupled heat and mass transfer processes occurring during both adsorption (discharging) and desorption (charging) phases. The model was validated against experimental data obtained under controlled thermo-hygrometric conditions.
The main contributions of this work can be summarised as follows:

- Development of a dynamic, layer-based numerical model capable of describing the transient thermo-hygrometric behaviour of a silica gel-packed bed.
- Experimental validation of the model under controlled laboratory conditions.
- Analysis of system performance under representative operating conditions for data centre waste heat recovery, including both adsorption and regeneration phases.

The results aim to provide insight into the operating behaviour of thermochemical storage systems under realistic low-temperature conditions, supporting their integration for waste heat recovery valorisation towards the decarbonisation of many energy systems and applications.

Nomenclature

Symbols

A, B, k, α	Constants of the isotherm of the material	*various*
E_a , k_0 , R	Constants to evaluate the kinetic constant of the material	*various*
Co	Courant number	
D	Diameter of the simulated sample	m
Dh	Enthalpy of the adsorption/desorption process	
dt	Temporal step of discretisation	s
dz	Spatial step of discretisation	m
i	General time of the simulation	
j	General layer of the simulation	
K	Kinetic constant of the material	1/s
L	Height of the simulated sample	m
$M_{mat,z}$	Mass of the material in a layer	kg
N_{layer}	Number of layers of the discretisation	
P	Pressure	Pa
Q_{proc}	Heat of the adsorption/desorption process	W
T	Temperature	°C
w	Velocity of airflow	m/s
W	Water uptake	kg/kg
x	Humidity ratio	kg/kg

Subscripts

eq	Equilibrium uptake
inlet	Inlet conditions
iso	At a certain isotherm
loc	Local equilibrium
max,iso	Maximum uptake
outlet	Outlet conditions

2 Materials and Methods

The following section describes the experimental setup adopted for the model validation and the development of the numerical model. In particular, the configuration of the test bench, the operating conditions, and the main assumptions underlying the modelling approach are presented, together with the formulation of the governing equations and their implementation in MATLAB.

2.1 Experimental setup for the model validation

For the experimental investigation, an open-cycle configuration was adopted, with air intake and exhaust directly connected to ambient conditions. In order to ensure controlled thermo-hygrometric conditions, a dedicated test bench was developed, capable of regulating both air temperature and relative humidity. A schematic representation of the system is reported in ***Figure 1***.

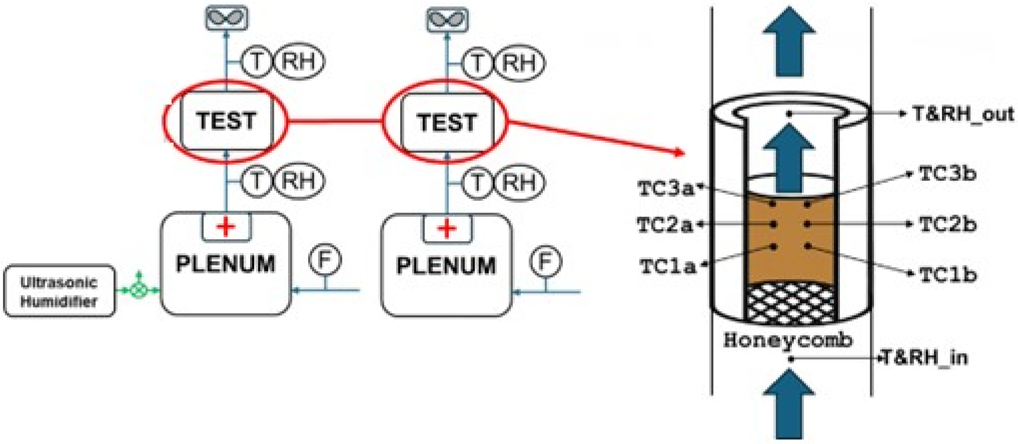

Figure 1. *Schematic representation of the test bench.*

The experimental setup consists of two separate air ducts, designed to reproduce the two operating phases of thermochemical energy storage: desorption (charging) and adsorption (discharging). In the desorption phase, corresponding to the charging process, ambient air is heated by electrically controlled resistances up to the desired setpoint temperature. Due to the temperature increase, the relative humidity of the air decreases significantly, creating favourable conditions for material regeneration. The heated air is then forced through the test section containing the thermochemical material, promoting water desorption. The outlet air, characterised by lower temperature and higher humidity, is discharged to the environment. In the adsorption phase, corresponding to the discharging process, ambient air is conditioned in a dedicated chamber to reach the desired relative humidity. The humid air then flows through the test section, where it is adsorbed by the material. As a result of the exothermic adsorption process, the air exits the reactor at a higher temperature and lower humidity. The test section consists of a packed bed of thermochemical material crossed by the air flow. The experimental setup is instrumented to measure temperature and humidity at multiple locations along the system, enabling the determination of inlet and outlet air conditions as well as the evolution of thermo-hygrometric variables during the process. Particular attention was devoted to the measurement of temperature gradients within the material, both along the flow direction and, where possible, across the bed. These measurements provide valuable information on adsorption kinetics and are essential for assessing key modelling assumptions, such as the one-dimensional approximation along the flow axis. To ensure the reliability of the experimental data, multiple tests were performed under controlled and repeatable conditions. The main boundary conditions varied during the experiments include inlet air temperature, relative humidity, air velocity, and the amount of material in the test section. For each configuration, repeated measurements were carried out to guarantee data consistency and to support the validation of the numerical model.

2.2 Modelling

2.2.1 Discretisation of the problem

The thermochemical reactor was modelled as a one-dimensional fixed bed along the air-flow direction. The packed bed, having a cylindrical shape of height L and diameter D, was divided into N_{layer} layers of equal thickness dz, each one representing a control volume containing both the moist air and the solid sorbent.The transient response of the bed was simulated by introducing a temporal discretisation with time step dt. Therefore, the numerical domain is defined by a spatial grid, corresponding to the centres of the layers, and by a temporal grid, corresponding to the successive simulation instants.

The air stream crosses the bed sequentially from the first to the last layer. For this reason, the outlet thermo-hygrometric conditions of each layer are assumed to be the inlet conditions for the following one. At each time step, the mass and energy balances are solved layer by layer, updating the local values of temperature, humidity ratio and adsorbed water content. The numerical model was implemented in MATLAB using an explicit time-marching procedure. The time step was selected consistently with the adopted spatial discretisation and the inlet air velocity w, through the Courant number:

$$Co = \frac{w \cdot dt}{dz} \tag{1}$$

The schematisation of the problem is shown in ***Figure 2***.

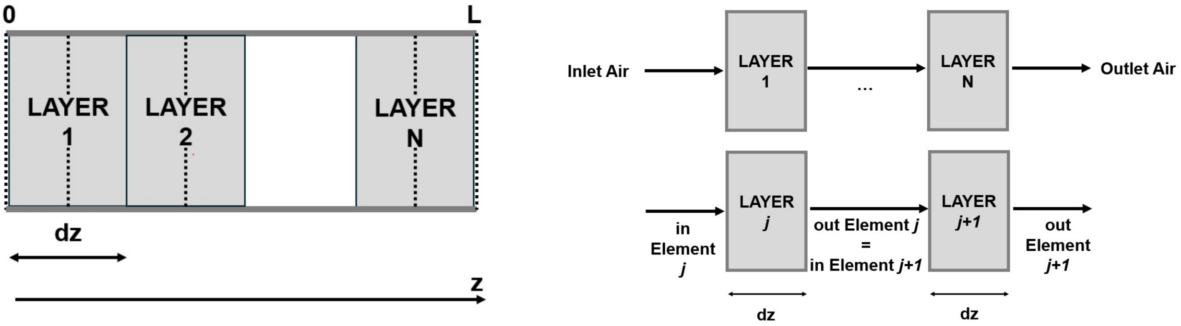

Figure 2. *Discretisation of the problem: spatial (left) and spatial-temporal (right).*

2.2.2 Model assumptions

To catch the relevant phenomena and keep the model computationally efficient, the following assumptions were adopted:

1 Adiabatic sample towards the external ambient.
2 Constant thermophysical properties of air and solid material.
3 One-dimensional transport along the bed height.
4 Uniform thermo-hygrometric conditions inside each control volume (layer).
5 Negligible radial gradients of temperature and water vapour concentration in the sample.
6 Heat exchange between air and solid is treated through a lumped formulation.
7 Local Thermal Equilibrium (LTE) between the solid and gas phase within each layer.
8 Adsorption/Desorption kinetics described by a first-order law.
9 Equilibrium uptake evaluated through a Sips isotherm.
10 Kinetic calculation based on the average between the inlet and the previous local conditions.

Under these assumptions, each layer is described by a single local temperature T_{loc}, a single humidity ratio x_{loc}, and a single adsorbed water content W.

2.3 Adsorption/Desorption equilibrium and kinetics

The water uptake of the silica gel, expressed as mass of adsorbed water per unit mass of dry material, was calculated as a time-dependent variable.

The time derivative of the water vapour uptake for layer j at time step i can be evaluated using a first-order kinetic expression:

$$\frac{dW}{dt} = K \cdot (W_{eq,iso} - W) \tag{2}$$

In this formulation, K is the kinetic constant and $W_{eq,iso}$ represents the equilibrium condition at a given temperature (isotherm). $W_{eq,iso}$ must therefore be updated at each time step for each layer. It can be expressed through different relationships for solid materials. Among the available models, the Sips formulation was selected.

$$W_{eq,iso} = W_{max,iso} \cdot A \cdot B \tag{3}$$

where the following relations are used:

$$A = \frac{(\alpha \cdot P_v)^k}{1 + (\alpha \cdot P_v)^k} \tag{4}$$

$$B = \frac{1}{\left(1 - \frac{P_v}{P_s}\right)^d} \tag{5}$$

The kinetic constant was evaluated through an Arrhenius-type expression:

$$K = k_0 \cdot e^{-\frac{R \cdot T}{E_a}} \tag{6}$$

where $k_0$is the pre-exponential factor, $E_a$is the activation energy, R is the universal gas constant, and $T$is the temperature (here expressed in Kelvin), $P_v$is the water vapour partial pressure, $P_{sat}$is the saturation pressure, and W_{max}, α, k, and d are temperature-dependent fitting parameters.

At each time step and for each layer, the kinetic term was evaluated using representative thermo-hygrometric conditions derived from the air entering the layer and the previous local equilibrium state. In this approach, the kinetic term is evaluated using averaged thermo-hygrometric conditions between the inlet conditions and the previous local conditions.

2.3.1 Mass balance

At each layer j, and at each time step i, the amount of vapour exchanged between air and material must be determined. The amount of heat exchanged between the air and the material must also be determined. For each control volume, the mass exchange of water vapour between the air stream and the solid sorbent is governed by the temporal variation of the uptake W.

$$W_j^i = W_j^{i-1} + \left(\frac{dW}{dt}\right)_j^i \tag{7}$$

The sign of dW/dtdetermines the operating mode of the system:

1 $dW/dt > 0$ adsorption (humidification), vapour is removed from the air.
2 $dW/dt < 0$ desorption (regeneration), vapour is released into the air.

Given the amount of water contained in the material, at each layer and at each time step, the vapour flow rate leaving could be calculated. This formulation naturally accounts for both adsorption and desorption processes. To ensure physical consistency, the exchanged vapour mass flow rate is limited so that it does not exceed the available vapour in the air stream during adsorption. The outlet humidity ratio could then be evaluated.

2.3.2 Energy balance

The heat exchange between the solid and the air is associated with the adsorption/desorption process and is proportional to the rate of uptake variation. The thermal power exchanged in each control volume is:

$$Q_{proc}{}_j^i = Dh_{proc} \cdot M_{mat,z} \frac{dW}{dt} \tag{8}$$

where $\mathrm{d}h_{proc}$is the specific enthalpy of adsorption/desorption (assumed equal in both processes).

The sign of dW/dtdetermines the thermal effect

3 $dW/dt > 0$ adsorption (humidification), exothermal process, heat is released to the air.
4 $dW/dt < 0$ desorption (regeneration), endothermal process, heat is removed from the air.

Assuming local thermal equilibrium between the gas and solid phases, a single energy balance is applied to each control volume. The updated local temperature is calculated as:

$$\frac{dE_{mat,z}}{dt} = Q_{proc}{}_j^i + Q_{air,in} - Q_{air,out} \tag{9}$$

This formulation accounts for:

1 The variation of energy of the solid phase (term of the left side).
2 The heat released/captured during adsorption/desorption.
3 The energy carried by the inlet air stream.
4 The energy carried by the outlet air stream.

3 Results and Discussion

This section presents the validation of the numerical model against experimental data and the analysis of system performance under representative operating conditions. The results are discussed in terms of thermo-hygrometric behaviour, energy performance, and implications for the practical use of thermochemical storage systems in low-temperature waste heat recovery applications.

3.1 Validation of the model

The developed numerical model was validated against experimental data obtained from a humidification test performed under ambient conditions (T_{inlet} = 26.6 °C and RH_{inlet} = 47.7 %). The dimensions of the sample are height *L* = 0.08 m and diameter *D* = 0.076 m, the sample is at an initial temperature of 20 °C, the air velocity is *w* = 0.33 m/s. The comparison was carried out in terms of outlet air temperature and humidity ratio as a function of time, as shown in ***Figure 3***.

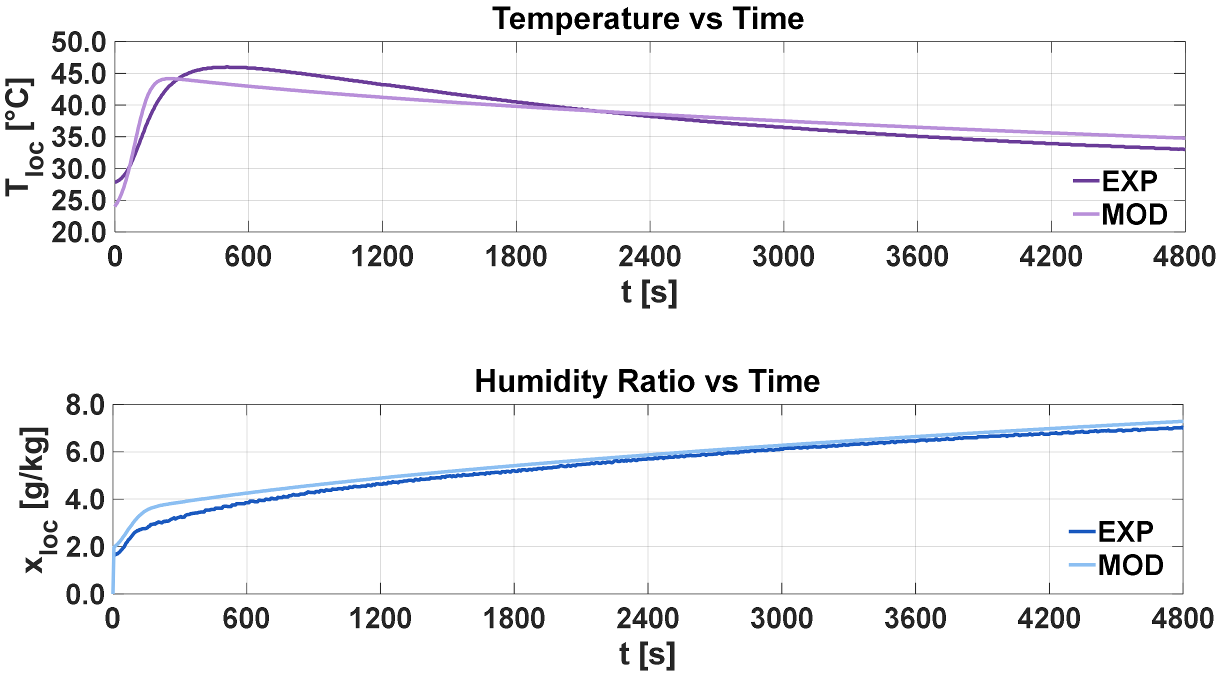

Figure 3. *Comparison between the results from model simulation and experimental test: outlet temperature (up) and outlet humidity ratio (down).*

Figure 3 (up) shows the comparison between experimental and simulated outlet air temperature. The model is able to accurately reproduce the main dynamic features of the process. In particular, the rapid temperature increase observed in the initial phase, associated with the exothermic adsorption of water vapour, is well captured. The model slightly overestimates the temperature peak and anticipates the initial transient, but the overall trend and the subsequent gradual decrease are in good agreement with the experimental data. The long-term behaviour is also satisfactorily predicted, with both experimental and numerical results showing a progressive reduction of the outlet temperature as the adsorption process approaches equilibrium conditions.
Figure 3 (down) presents the comparison in terms of outlet humidity ratio. The numerical model correctly reproduces the overall increase in humidity ratio over time, corresponding to the progressive saturation of the material. A slight discrepancy is observed in the early stages, where the model predicts a faster increase compared to the experimental data. However, the agreement improves significantly as time progresses, and the final values are closely matched.
The observed deviations in the initial transient can be attributed to model simplifications, such as the assumption of local thermal equilibrium and the use of a lumped formulation for each layer, which may not fully capture intra-particle mass transfer resistances and non-uniformities within the bed. Overall, the model demonstrates a satisfactory capability to predict both thermal and mass transfer behaviour of the system, making it suitable for further parametric analyses and performance evaluation under different operating conditions.

3.1.1 Adsorption under representative winter conditions

A representative adsorption case was simulated to evaluate the performance of the thermochemical storage system under winter conditions consistent with the Varna (Bulgaria) demo site. The inlet air was set at representative conditions of cold and humid conditions during the heating season (T_{inlet} = 10.0 °C and RH_{inlet} = 80.0 %). The dimensions of the sample are height L = 0.08 m and diameter D = 0.076 m, the sample is at an initial temperature of 20 °C, the air velocity is w = 0.33 m/s. Some results in terms of outlet temperature, outlet humidity ratio and average uptake are shown in ***Figure 4***.

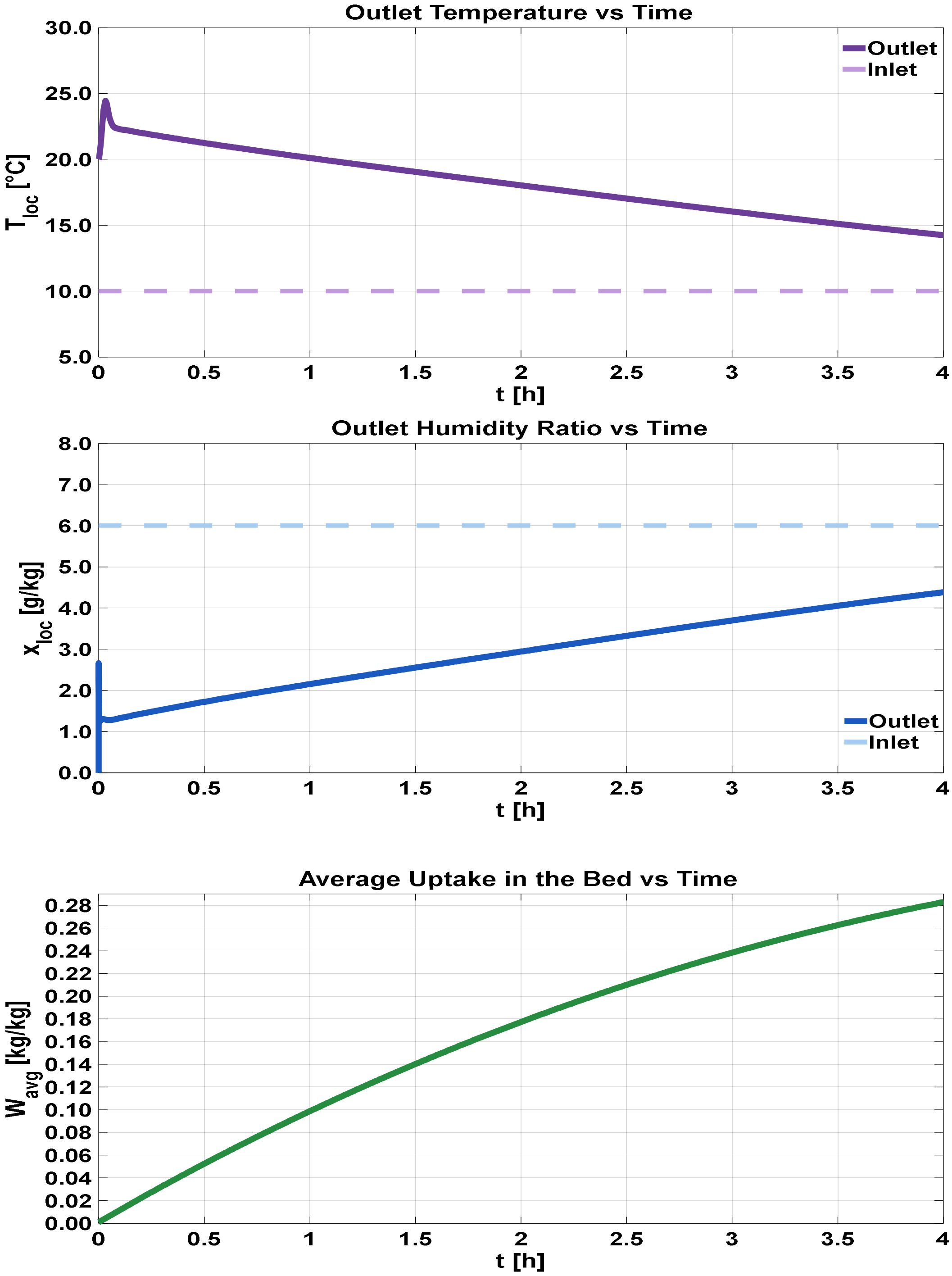

Figure 4. *Results of the simulation for the adsorption process: outlet temperature (up), outlet humidity ratio (middle), average water uptake (down).*

Figure 4 (up) shows the temporal evolution of the outlet air temperature compared to the inlet value. At the beginning of the process, a rapid temperature increase is observed, driven by the exothermic adsorption of water vapour within the silica gel bed. The outlet temperature quickly reaches a peak of approximately 24–25 °C, corresponding to a temperature lift of about 14–15 °C with respect to the inlet air. Following this initial transient, the outlet temperature progressively decreases over time, approaching the inlet condition. This behaviour reflects the gradual reduction of the adsorption rate as the material becomes increasingly saturated. The thermal effect becomes less pronounced as the driving force for mass transfer decreases, leading to a continuous decline in the useful temperature lift.

The outlet humidity ratio, shown in ***Figure 4*** (middle), confirms this behaviour. A strong initial reduction is observed, with the outlet humidity dropping significantly below the inlet value due to the high adsorption capacity of the material. As the process evolves, the outlet humidity ratio gradually increases, approaching the inlet condition as the material approaches saturation.

The evolution of the average uptake in the bed, reported in ***Figure 4*** (down), provides further insight into the process dynamics. The uptake increases continuously over time, with a relatively steep slope in the initial phase, followed by a more gradual increase. Notably, the uptake does not reach an asymptotic value within the simulated time, indicating that additional adsorption capacity is still available in the material.

However, despite the residual adsorption potential, the corresponding thermal effect becomes progressively negligible. This highlights an important aspect for practical applications: extending the operating time beyond a certain point does not lead to a significant increase in useful thermal output, even though the material is not fully saturated. Therefore, an optimal operating window exists in which the majority of the useful heat release is achieved, while further operation results in diminishing returns.

Overall, the results demonstrate that silica gel-based thermochemical storage systems can effectively exploit humid air streams at low temperature levels, providing a substantial temperature lift during the initial phase of operation. At the same time, they underline the importance of properly defining the operating time in order to maximise system efficiency under realistic winter conditions.

From a quantitative perspective, the system exhibits a maximum temperature lift of approximately 14.4 °C, confirming the strong thermal effect associated with the initial adsorption phase. The temperature difference progressively decreases during operation, reaching values around 4 °C at the end of the simulated period. The humidity ratio variation further supports this behaviour, with a maximum reduction of about 0.006 kg/kg in the initial phase, followed by a gradual decrease in the mass transfer rate as the material approaches saturation.

The overall uptake variation of the bed is equal to 0.28 kg/kg, indicating that a significant fraction of the adsorption capacity of the material is effectively exploited. However, despite the relatively high uptake variation, the corresponding thermal effect becomes progressively negligible over time.

This result highlights a key design implication: although the material is not fully saturated at the end of the process, extending the operating time does not lead to a substantial increase in useful thermal output. Most of the recoverable energy is released during the initial phase, suggesting that the system should be operated within an optimal time window to maximise efficiency.

In terms of energy performance, the total thermal energy exchanged during the process is approximately 210 kJ, with an average thermal power of about 14.6 W and a peak value close to 26 W. These results confirm the suitability of the system for low-temperature heat recovery applications, particularly when integrated into systems characterised by continuous or quasi-continuous operation.

3.1.2 Desorption under representative regeneration conditions

A representative regeneration case was simulated to evaluate the charging phase of the thermochemical storage system under conditions compatible with low-grade waste heat recovery. The inlet air was set at 65 °C and 10 % relative humidity, while the packed bed was assumed to be initially loaded with water, with an average initial uptake of about 0.28 kg/kg. Some results in terms of outlet temperature, outlet humidity ratio and average uptake are shown in ***Figure 5***.

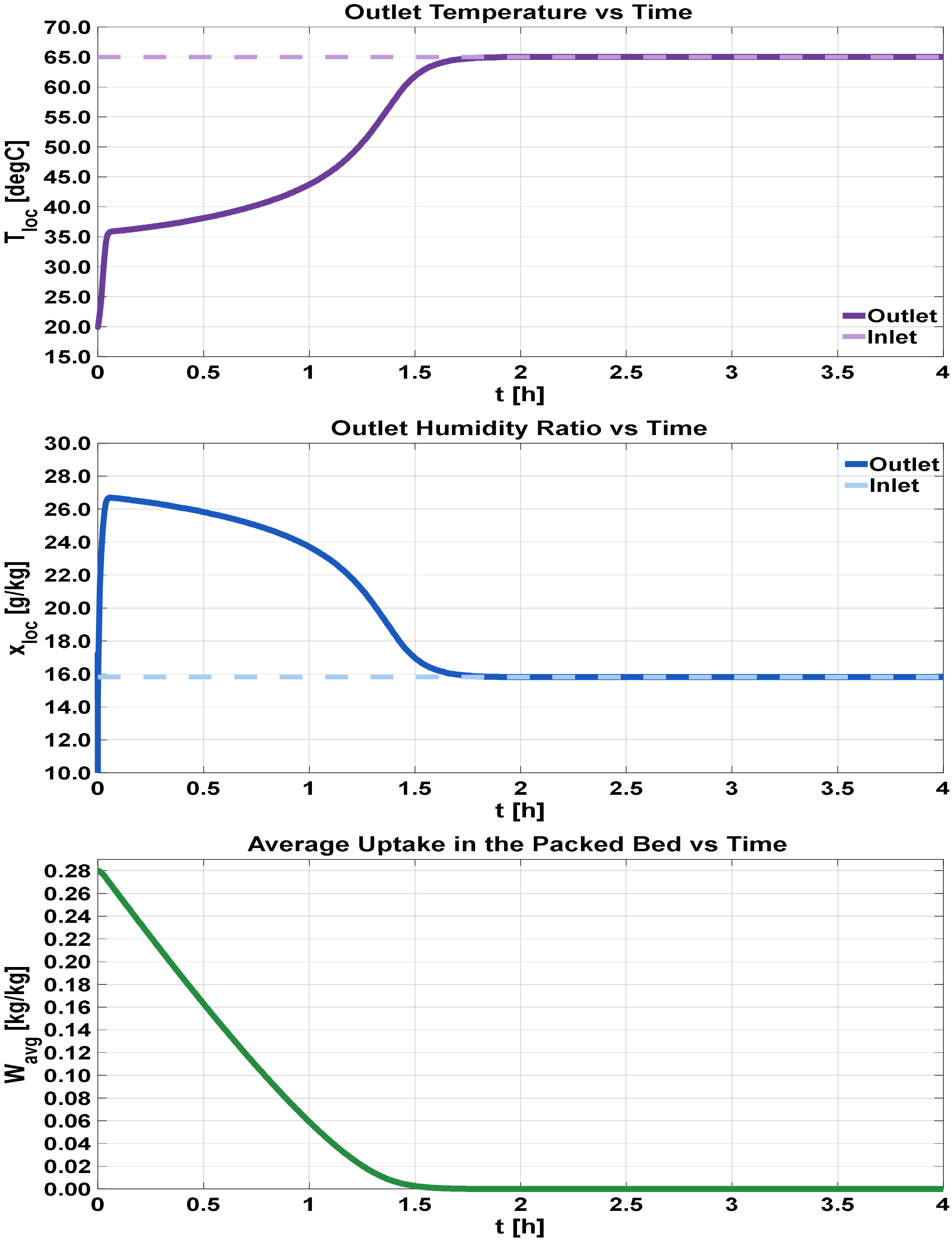

***Figure 5**. Results of the simulation for the desorption process: outlet temperature (up), outlet humidity ratio (middle), average water uptake (down).*

Figure 5 (up) shows the evolution of the outlet air temperature during the regeneration process. At the beginning of the simulation, the outlet temperature is significantly lower than the inlet temperature, as the incoming hot air transfers heat to the packed bed and provides the energy required for water desorption. As the process progresses, the outlet temperature gradually increases and approaches the inlet value, indicating the progressive reduction of the endothermic effect associated with desorption. The maximum temperature difference with respect to the inlet air reaches about 45 °C in absolute terms, confirming the strong thermal demand of the initial regeneration phase. Afterwards, the temperature difference rapidly decreases as the material becomes progressively dried.

The outlet humidity ratio, reported in ***Figure 5*** (middle), exhibits the opposite behaviour. At the beginning of the process, the outlet air becomes significantly more humid than the inlet stream because of the release of water vapour from the sorbent. Then, the outlet humidity ratio progressively decreases and approaches the inlet value as the desorption process weakens. The maximum increase in humidity ratio is approximately 0.011 kg/kg, highlighting the strong vapour release occurring in the first part of the process.

The average uptake evolution in ***Figure 5*** (down) clearly shows the progressive regeneration of the material. Starting from an initial value close to 0.28 kg/kg, the uptake decreases rapidly and approaches zero after about 1.5–1.7 h, indicating that the material is almost completely regenerated within the simulated time. The overall uptake variation is equal to -0.28 kg/kg, confirming the nearly complete removal of the water initially stored in the silica gel.

From an energetic point of view, the regeneration process requires approximately 218 kJ of thermal energy, with an average thermal power of about 15 W and a peak value close to 81 W. These results indicate that the charging process is characterised by a strong initial thermal demand, followed by a rapid reduction of the required power once the material has been largely regenerated.

Overall, the results demonstrate that silica gel can be effectively regenerated at temperatures around 65 °C, which are compatible with low-grade waste heat sources. At the same time, the results indicate that most of the useful regeneration effect is concentrated in the initial phase, while extending the process after the material has been substantially dried provides only limited additional benefit.

4 Conclusions

The present work investigated the performance of a silica gel-based thermochemical energy storage system under representative operating conditions for low-grade waste heat recovery. A dynamic model implemented in MATLAB was developed and validated against experimental data, and subsequently used to analyse both adsorption (discharging) and desorption (charging) phases.

The results highlight the potential of thermochemical storage systems for applications involving low-temperature heat sources, such as data centre waste heat recovery.

The main findings of the study can be summarised as follows:

1. The adsorption process under winter conditions (10 °C, 80% RH) provides a significant temperature lift, with a maximum increase of approximately 14.4 °C, demonstrating the capability of the system to upgrade low-temperature heat streams.
2. A substantial reduction in outlet humidity ratio is observed during adsorption, with a maximum decrease of about 0.006 kg/kg, confirming the strong sorption capacity of silica gel under humid conditions.
3. The material exhibits a high uptake variation of approximately 0.28 kg/kg, indicating an effective utilisation of the storage capacity. However, the results show that most of the useful thermal effect is concentrated in the initial phase.
4. The total thermal energy exchanged during adsorption is about 210 kJ, with an average thermal power of approximately 15 W, confirming the suitability of the system for continuous or quasi-continuous low-grade heat recovery applications.
5. During the regeneration phase (65 °C, 10% RH), the system requires a comparable amount of energy, approximately 218 kJ, highlighting the consistency of the thermochemical cycle.
6. The desorption process is characterised by a strong initial thermal demand, with a peak power close to 81 W, followed by a rapid decrease as the material becomes progressively dried.
7. The silica gel bed is shown to be almost completely regenerated within about 1.5–2 hours, with a total uptake variation of approximately -0.28 kg/kg, enabling the recovery of the full storage capacity.

Overall, the combined analysis of adsorption and desorption processes demonstrates the feasibility of using silica gel-based thermochemical storage systems for the recovery and reuse of low-grade waste heat. The results also underline the importance of defining an optimal operating time window, as both charging and discharging processes exhibit strong transient behaviour with most of the useful energy exchange occurring in the initial phase.

These findings support the integration of thermochemical energy storage technologies into energy systems characterised by low-temperature heat sources, contributing to improved energy efficiency and to the development of sustainable solutions for waste heat valorisation.

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