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Technical Note

Numerical analysis and evaluation of an open-type thermal storage system using composite sorbents

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ABSTRACT

A family of composite sorbents has been acknowledged as promising thermal storage materials for low grade thermal energy storage owing to its high specific storage capacity and low regenerating temperature. This paper reports a simplified numerical model aiming to determine the dynamic characteristics of the composite sorbents and evaluate the specific capacity and COP of the open-type thermal energy storage system. The computational results were validated with the experimental measurements carried out on an open-type thermal energy storage set-up filled with composite sorbents. By using the simplified numerical model, the dynamic characteristics of the composite sorbents in the thermal energy storage process were determined. The effects of the composite sorbents and the operating parameters on thermal energy storage system performance were also evaluated.

1. Introduction

Thermal energy storage (TES) is an advanced technique to correct the mismatch between the supply and demand of energy [1–3]. The thermo-chemical technology based on water sorption/desorption on porous materials appears to be a promising candidate for TES since little heat loss occurs over the sorption storage process because of the temporally dissociation with adsorbate from adsorbent. Recently, a family of composite sorbents has been developed by impregnating the porous adsorbents to the aqueous solution of hygroscopic salts so as to improve their sorption and TES capacity [4–7]. The dynamic characteristics of the composite sorbents differ from the silica gels and zeolites. In point of determining the dynamic TES characteristics and optimizing the TES system performance, it is time- and energy-consuming to measure the TES characteristics through experimental investigations for different composite sorbents under various operating conditions. It will be helpful to establish a facile and feasible model and carry out numerical tests to optimize TES performance [8]. The majority of modeling undertaken so far concentrates on the pure adsorbents, e.g. silica gels and zeolites. Little work has been directed towards the dynamic TES characteristics of the composite sorbents by using a facile and feasible numerical model. The aim of this paper is to determine the dynamic characteristics of the composite sorbents and evaluate the performance of the open-type sorption TES through numerical tests based on a facile and feasible model. The simplified model was first validated by experimental measurements for the composite sorbents. Numerical tests were then carried out to determine the dynamic characteristics and evaluate the sorption TES performance.

2. Mathematical model

A typical open-type TES system mainly consists of an adsorber, a humidifier, and a condenser [6,7]. The adsorber is the key component of the sorption storage system where water is adsorbed on or desorbed from the sorbent. In order to simplify the model, the following assumptions are made: (a) the heat capacity of adsorbate in the adsorbed state is equal to that of the liquid phase; (b) the specific heat and density of dry composite sorbents are constant; (c) the composite sorbents are uniformly packed, and the adsorber can be considered as a packed bed with a certain porosity. It should be noted that the assumption (a) is feasible for an open-type TES system in this present study although the difference of the heat capacity between the adsorbate in the adsorbed state and that in liquid phase could be significant at high pressure and low temperature [9].

2.1. Energy conservation equation

The conservation equation of energy for the composite sorbents is

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$$m_{cs}\left(c_{p,dcs}+c_{p,w}w+\frac{m_b c_{p,b}}{m_{cs}}\right)\frac{\partial T_{cs}}{\partial t}-m_{cs}Q_{st}\frac{\partial w}{\partial t} = k_{cs}A_{cs}L\left(\frac{\partial^2 T_{cs}}{\partial x^2}+\frac{\partial^2 T_{cs}}{\partial y^2}+\frac{\partial^2 T_{cs}}{\partial z^2}\right)+\dot{S}_d \quad (1)$$

where m_{cs} and m_b are the mass of the composite sorbents and the adsorber heat exchanger, respectively. $c_{p,dcs}$, $c_{p,w}$, $c_{p,b}$ are the specific heat of the dry composite sorbents, water and the adsorber heat exchanger, respectively. w is the amount of water adsorbed on the composite sorbents, Q_{st} the isosteric heat of sorption, k_{cs} thermal conductivity of the composite sorbents, A_{cs} the heat transfer area for composite sorbents, L the length of the adsorber. $\dot{S}_d$ is the inner heat source item in terms of the heat input power (q_{in} = 4 kW at $T_{cs} < T_{pr}$, $q_{in} = 0$ at $T_{cs} \geqslant T_{pr}$, where T_{cs} and T_{pr} are the temperatures of the composite sorbents and the preset temperature for regenerating composite sorbents, respectively.) to regenerate the composite sorbents during the heat charging process. It is zero during the heat discharging process.

The conservation equation of energy for the air is

$$m_a c_{p,a}\frac{\partial T_a}{\partial t} = -\dot{m}_a c_{p,a}\frac{\partial T_a}{\partial x}+k_a A_a L\left(\frac{\partial^2 T_a}{\partial x^2}+\frac{\partial^2 T_a}{\partial y^2}+\frac{\partial^2 T_a}{\partial z^2}\right) \quad (2)$$

where, m_a, $\dot{m}_a$, $c_{p,a}$, k_a and A_a are the mass, mass rate, specific heat, thermal conductivity and heat transfer area of the air, respectively.

2.2. Adsorption equations

The mass transfer resistance of the inter-void space in the composite sorbents may be neglected. A linear driving force equation is introduced to determine mass transfer resistance of the composite sorbents. Thus the rate of change of moisture content is proportional to the difference between the equilibrium moisture content and the actual one.

$$\frac{\partial w}{\partial t} = h_m(w_{eq}-w) \quad (3)$$

where w_{eq} is the equilibrium amount of water adsorbed on the composite sorbents. h_m is the mass transfer coefficient and determined:

$$h_m = \frac{15D_s}{R_p^2} \quad (4)$$

where R_p is the average radius of composite sorbents. D_s is the surface diffusivity and can be expressed as a function of temperature:

$$D_s = \frac{1}{\xi}D_{s,0}\exp\left(-\frac{Q_{st}}{RT}\right) \quad (5)$$

where $D_{s,0}$ is the diffusivity with a constant value of 1.6×10^{-6} m^2/s. ξ is the bend factor relevant to the pore length of the composite sorbents.

2.3. Thermodynamic characteristics

The specific heat of composite sorbents is relevant to the amount of water adsorbed:

$$c_{p,cs} = c_{p,cs,dry}+wc_{p,w} \quad (6)$$

The heat of adsorption for composite sorbents can be obtained from the measurement of the sorption characteristics. It can also be fitted with a polynomial function of the amount of water adsorbed:

$$Q_{st} = a_4w^4+a_3w^3+a_2w^2+a_1w+a_0 \quad (7)$$

where the constants a_i (i = 0, 1–4) can be calculated by fitting the curve of heat sorption. For the composite sorbents prepared by impregnation the $CaCl_2$ solution with the mass concentration of 40% into the porous silica gel, the values of the constants has been calculated in our previous art [7] as: $a_4 = 1139$, $a_3 = -3307$, $a_2 = 3459$, $a_1 = -1620$, $a_0 = 2727$.

2.4. TES performance

The total heat input to regenerate the composite sorbents may be obtained by integrating of heat power over the heat charging period:

$$Q_{in} = \int_{chg} q_{in}\,dt \quad (8)$$

As the minimum temperature of the available heat output from the adsorber by air is preset to T_{avl}, the total heat output by the air over the discharging process can be calculated as

$$Q_{out} = \int_{dchg} c_{p,a}\cdot\dot{m}_a\cdot(T_{out}-T_{avl})dt \quad (9)$$

The specific TES capacity of composite sorbents can be accordingly calculated as

$$c_{ES} = \frac{Q_{out}}{m_{cs}} \quad (10)$$

The COP of the TES system is defined as

$$COP = \frac{Q_{out}}{Q_{in}} \quad (11)$$

3. Numerical solution and experimental validation

The governing equations were solved by using the finite volume method (FVM). The method imply that the integral conservations of quantities such as energy, mass and momentum are exact over any group of control volumes. The calculation domain was first divided into a finite number of non-overlapping control volumes. Then the discrete governing equations were derived over each control volume and time interval and numerically solved by using Fortran code.

An experimental open-type sorption storage set-up was built in Southern China to measure its TES performance to validate the computational results from the simplified numerical model. The dimensions of the adsorbent heat exchanger of the set-up are 0.8 m (length) × 0.3 m (width) × 0.4 m (height) [6,7]. The plat-fin type heat exchanger was adopted to enhance the heat transfer. During the heat discharging process, the air at the inlet of the adsorber was controlled at approximately 15 °C and 0.014 g water per gram dry sorbent by a dehumidifier. The available minimum temperature (T_{avl}) of the outlet air from the adsorber was preset to 30 °C. The data collection in the experimental study was achieved using the data acquisition system equipped with thermocouples, pressure sensors and flow meters located at the desired measurement points. The temperatures were measured by thermocouples with errors of ±0.1 °C. The air humidity was measured by a Vasala dew-point sensor with errors of ±3%. The operation of the experimental set-up was controlled by a PLC (Programmable Logic Controller).

The composite sorbents were first pelleted by using the binder and approximately 40 kg composite sorbents were then packed in the adsorber. The dynamic characteristic of the open-type adsorption thermal energy system packed with four kinds of composite sorbents (viz. CS1, CS2, CS3, and CS4) prepared by impregnating the mesoporous silica gel with the $CaCl_2$ solution with different concentrations [6,7] were investigated. Fig. 1 shows an example of the experimental and computational results of the temperature

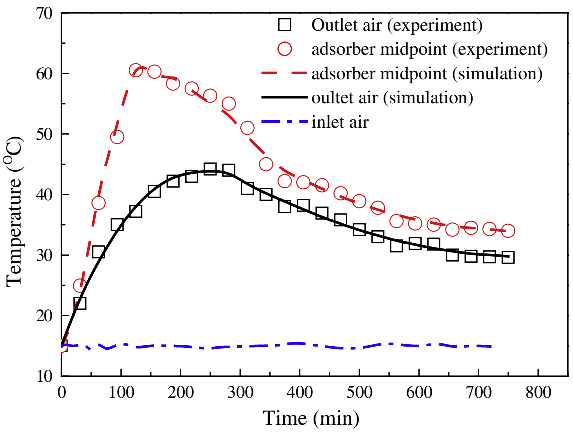

Fig. 1. Comparison of computational and experimental results of the temperature in the open-type adsorber.

during the heat discharging process in the open-type thermal storage system filled with the composite sorbent CS2. It can be observed that the experimental and simulated results agree quite well. Based on the simplified numerical model the numerical tests for four types of composite sorbents under various TES operating parameters were carried out to determine the dynamic characteristics of the composite sorbents and evaluate the performance of the open-type sorption TES.

4. Results and discussion

4.1. Numerical analysis of dynamic characteristics in sorption thermal energy storage process

In the heat discharging process, moist air flows through the adsorber and the water vapor in the moist air is adsorbed by the composite sorbents packed in the adsorber. The dynamic variation of the moisture content of the outlet air from the adsorber is shown in Fig. 2. It can be observed that the outlet air was deeply dehumidified at the starting process due to the high sorption capacity of the composite sorbents. Then the outlet air moisture increased significantly with the progress of the sorption process. Fig. 2 also indicates that the composite sorbents with higher $CaCl_2$ content yield lower moisture content of the outlet air in most part of the sorption process because of their greater sorption capacity. However, after a long time (viz. $t > 800$ min) the difference of the moisture content of the outlet air for different composites sorbents decreases even to be zero because of the great amount water adsorbed on the composite sorbents up to sorption saturation.

Fig. 3 indicates that the temperature of the outlet air increases fast in the initial heat discharging process since the composite sorbents were heated by the sorption heat. The highest temperature of the outlet air occurs at about 200 min. Then the temperature of the outlet air decreased slowly to 30 °C which was preset as the minimum temperature for available heat since the sorption capability of the composite sorbent slowly degrades. The composite sorbents with higher $CaCl_2$ content yield higher temperature of the outlet air. It is understandable the composite sorbents with higher $CaCl_2$ content can adsorb more water vapor from the air and consequently release more heat in most part of the heat discharging process.

4.2. Numerical evaluation of specific TES capacity and COP of sorption thermal energy system

Figs. 4 and 5 present the numerical evaluation of the specific TES capacity and COP of the open-type sorption TES for different composite sorbents by using the simplified model, respectively. Fig. 4 indicates that the specific TES capacity of the composite sorbents increases noticeably as the regenerating temperature is increased from 80 to 100 °C. The higher regenerating temperature induces greater desorption amount in the regenerating process, which yields higher absorption capacity of the composite sorbents in the next sorption cycle. It is very interesting to note that the specific TES capacity of the composite sorbents CS3 and CS4 is up to 1 kJ/g by using appropriate regenerating temperatures. It is significantly higher than that of the pure silica gel and zeolite adsorbent with specific TES capacity of approximately 0.35 kJ/g and phase change materials with specific TES capacity of approximately 0.2 kJ/g.

Fig. 5 indicates that the COP of the TES system decreases as the regenerating temperature is increased. It is understandable that the COP of the TES system is dependent on the ratio between the total heat input to and the total heat released from the adsorber. Therefore, the optimal regenerating temperature should be determined by integrally considering the requirements of both the specific capacity and efficiency.

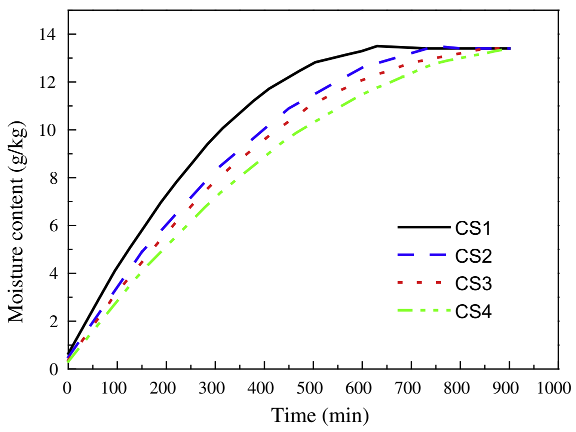

Fig. 2. Numerical analysis of moisture content of outlet air in heat discharging process for different composite sorbents.

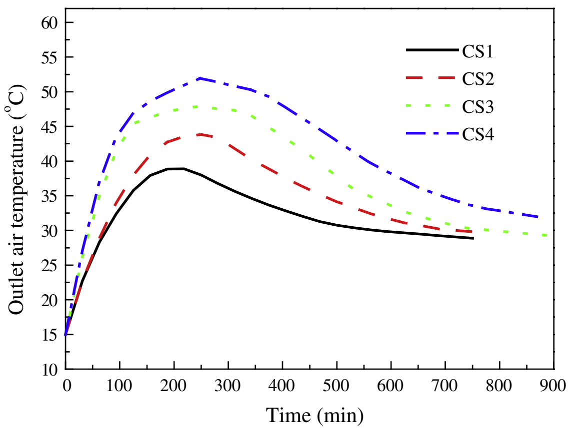

Fig. 3. Numerical analysis of temperature of the outlet air in heat discharging process for different composite sorbents.

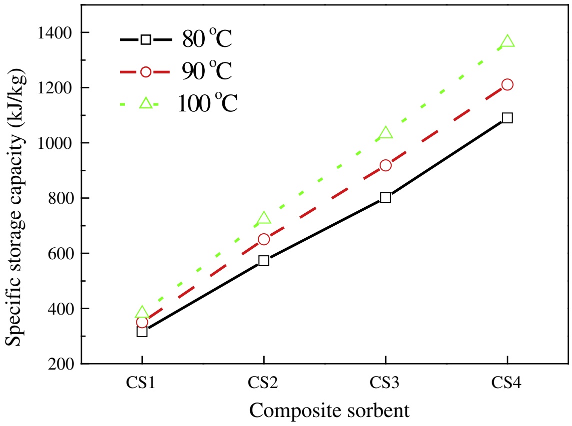

Fig. 4. Numerical evaluation of specific TES capacity of the sorption TES system for different regenerating temperatures.

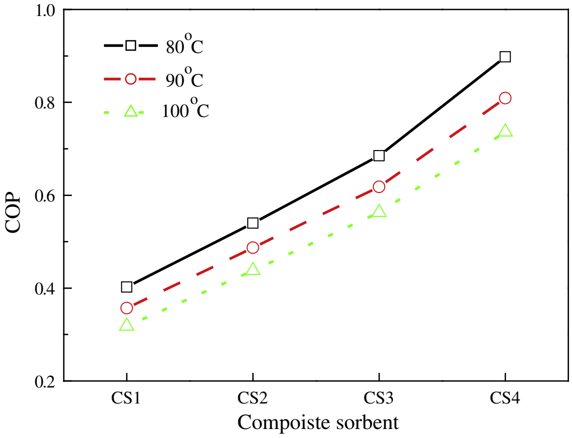

Fig. 5. Numerical evaluation of COP of the sorption TES system for different regenerating temperatures.

5. Conclusions

This paper presented numerical tests to evaluate the dynamic characteristics of the composite sorbents in an open-type TES system based on a simplified numerical model. The results indicate that the nature of composite sorbents (e.g. the $CaCl_2$ content) played a key role on the dynamic characteristics in the TES process. A high TES capacity of up to 1 kJ/g could be obtained for the composite sorbents CS3 and CS4 at the preset available supply temperature of 30 °C and the regenerating temperature of 90 °C. The specific TES capacity increased noticeably while the COP of the TES system decreased as the regenerating temperature was increased from 80 to 100 °C.

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