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Design of a thermochemical heat storage system for tap water heating in the built environment

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1. Abstract

Replacing the use of fossil fuel by solar energy, as one of the most promising sustainable energy sources, is of high interest, because of climate change and depletion of fossil resources. However, to reach high solar fractions and to overcome the mismatch between supply and demand of solar heat, storage of solar energy is necessary. A reliable method for long term heat storage is to use thermochemical materials, TCMs. The heat storage process is based on a reversible adsorption-desorption reaction of water vapor on the TCM, which is exothermic in one direction and endothermic in the reverse direction. In this research, Zeolite 13X is used as TCM. The system is an open sorption heat storage system for providing hot tap water. In the experimental test setup, the humid air is provided in a bubble column by blowing air from bottom of the column. The exothermic hydration process starts with humid air entering into a packed bed reactor filled with zeolite 13X. The reactor is a vertical cylindrical tank which is made of steel; it has a layer of Teflon inside and has a layer of insulation outside. The temperature profile in the reactor is measured as a function of time both along the flow direction and perpendicular to the flow by thermocouples. In addition, input and output temperatures and humidity are measured. In the resulting adsorption reaction between water vapor and TCM, energy is released. This released energy heats up the air flow which passes through the reactor and the hot output air flow is used to heat up the water in a water tank. The water tank is also a vertical cylindrical tank which is made of steel and has a layer of insulation outside. The hot output air from the reactor passes through a coiled tubing inside the water tank to heat up water. The temperature of the water in the tank is measured at two different heights. A problem in open solid sorption systems using air as heat transport medium is the limited temperature step which can be achieved in the sorption bed. In the present study this problem is solved using a heat recovery system enabling higher output air temperatures. The residual heat in the exhaust air is used to preheat the reactor inflow, in an air-to-air heat exchanger. In the endothermic dehydration process, the hydrated zeolite is dried with hot air. In this study, a lab-scale prototype TCM based heat storage system is designed and optimized, which, by making use of a heat recovery loop, is able to provide hot tap water. Results of the experimental investigation on charge-discharge cycles will be presented.

Keywords: TCM based seasonal heat storage system; domestic hot water; adsorption and desorption; fixed bed reactor; heat recovery; Zeolite 13X



2. Introduction

According to the International Energy Agency (IEA), the building sector is the largest consumer of energy and accounts for approximately 40 % of the world's total primary energy consumption, which is equal to 2794 million tons of oil equivalent (Mtoe), and 24 % of the world's total CO₂ emission [1]. Therefore, significant reductions in fossil fuel consumption are possible by using renewable energy sources in this sector.

In recent years, studies have been done to reach a low-energy building concept. The passive house concept, which was developed first in Germany [2], is one of the leading concepts. Some other low-energy demonstration projects are described in [3] and [4]. Net zero energy building projects demonstrate that reducing total energy consumption of a house is possible using new innovative solar energy technologies, which in the case of increase in price of energy would be profitable compared to conventional energy-saving technologies [5]. Solar energy is one of the most promising sustainable energy sources for replacing fossil fuels. It can be used in residential buildings by means of different methods, such as solar collectors, PV panels and passive design. Since both the solar irradiation and the energy demand show large variations during a year that are asynchronous, energy storage is necessary to make effective use of the available solar energy [6].

In the case of using solar energy in the built environment, long-term heat storage is needed to overcome the seasonal mismatch between heating demand and solar energy supply. Conventional heat storage methods have considerable heat losses and relatively low energy storage density. Heat storage by means of a reversible reaction ($A + B \leftrightarrow AB + Heat$) has comparatively higher energy storage density and almost no heat loss. Heat generated by a solar collector during summer can be stored in an endothermic dissociation reaction of a thermochemical material into two components (charging), and the energy stored in this way can be released during winter by the reverse exothermal reaction between the components (discharging). An interesting reactant should be low cost, non-toxic, non-corrosive and stable with high energy storage density [7]. A comparison between the different materials is done by Shigeishi [8] which shows a candidate fulfilling these requirements except the cost is zeolite 13X which can adsorb and desorb water vapor in an efficient and reversible way.

As it is shown in Figure(1), two types of sorption system can be distinguished: open and closed systems. In an open system, moist air from ambient is used to hydrate the material, but in a closed system, no material is exchanged with the ambient [9]. In literature, different closed sorption systems can be found. The MODESTORE project of the AEE/Intec (AEE – Institute for Sustainable Technologies, Austria) [10] works with silica gel and water which creates only a small temperature step of 10 K. Weber and Dorer analyzed long-term heat storage using a closed sorption system with NaOH and water as the working pair and compared the results with a conventional storage system, focusing on system volume [11]. Open sorption systems are operated in an open loop coupled to the ambient. Therefore water is used as adsorptive. An air stream is transporting water vapor and heat in and out of the packed bed of solid adsorbent [12]. In ITW (Institute of Thermodynamics and Thermal Engineering), two open systems are developed based on extruded zeolite honeycomb monolith [13] and segmented reactor concept [14]. Zondag et al. [15] characterized magnesium sulphate as a storage medium and examined the cycling behavior of MgSO₄ and the dehydration temperature of the reactant.

The most important part of the system which can provide such long-term heat storage for a residential building is the reactor. The advantage of using a fixed-bed reactor is the low need of auxiliary energy in comparison with other types of reactors such as fluidized bed or screw reactors. Here, an open atmospheric packed bed reactor on lab-scale is chosen for the experiments because of its simplicity and low costs compared to other types of systems [16].

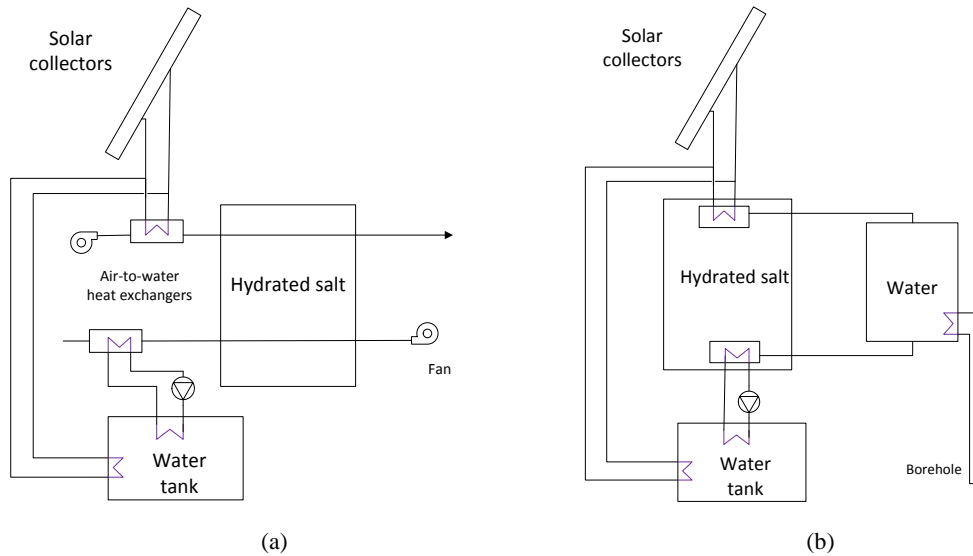


Figure (1): two types of sorption system: (a) open and (b) closed

The purpose of this study is to investigate the applicability of thermochemical heat storage for providing hot tap water in the built environment. A lab-scale thermochemical heat storage system is designed and tested. Humid air flows through the reactor filled with zeolite 13X and depending on the air temperature and humidity adsorption takes place leading to the release of the stored energy. The performance of the system is studied experimentally and is improved by implementing heat recovery and reducing the heat losses from the side wall of the reactor.

3. Experimental setup

An open sorption system by application in built environment generally consists of a solar collector, a borehole system as the humidifier, a sorption tank for long term energy storage and a water vessel for short term energy storage. In order to simulate the thermo-chemical heat storage system, a test setup is designed, which consists of a hydration loop and a dehydration loop. In Figure(2), a schematic view of the whole setup is shown. In this experimental test setup, the air flow is taken from the lab compressed air system, delivering air at the pressure of 7.5 bar and small relative humidity of 2.5 % at 25 °C. The flow rate is regulated by a flow controller. For hydration, air blows from bottom of a bubble column as a humidifier module in order to simulate the borehole. For dehydration, a heater is used in order to simulate the solar collector in the setup. The air flow passes through the heater and the heated air goes to the reactor. At the beginning of the hydration experiment, some time is needed for the system to be stabilized; during the stabilization time, the flow is drained to the ambient through the dehydration loop output as a blow off pipe.

The reactor is the main part of the setup and most of the measurements are done in this part. Figure(3) shows a schematic view of the reactor. The inner shell of the reactor body is made of PTFE (Teflon), because of its low thermal conductivity. The outer layer is made of stainless steel and a 10 mm layer of Armaflex HT insulation is used around the reactor. The air enters the reactor from the top side and leaves the reactor at the bottom. There is a diffuser at the top of the reactor in order to spread the inlet flow profile and a filter is placed at the bottom of the reactor in order to retain the material beads in the reactor. A stainless steel wired mesh with a mesh opening of 820 micrometer is used as a filter and is pressed between two rings of PEEK material in order to be fixed in its place. Properties of the used materials in the reactor body are presented in Table(1).

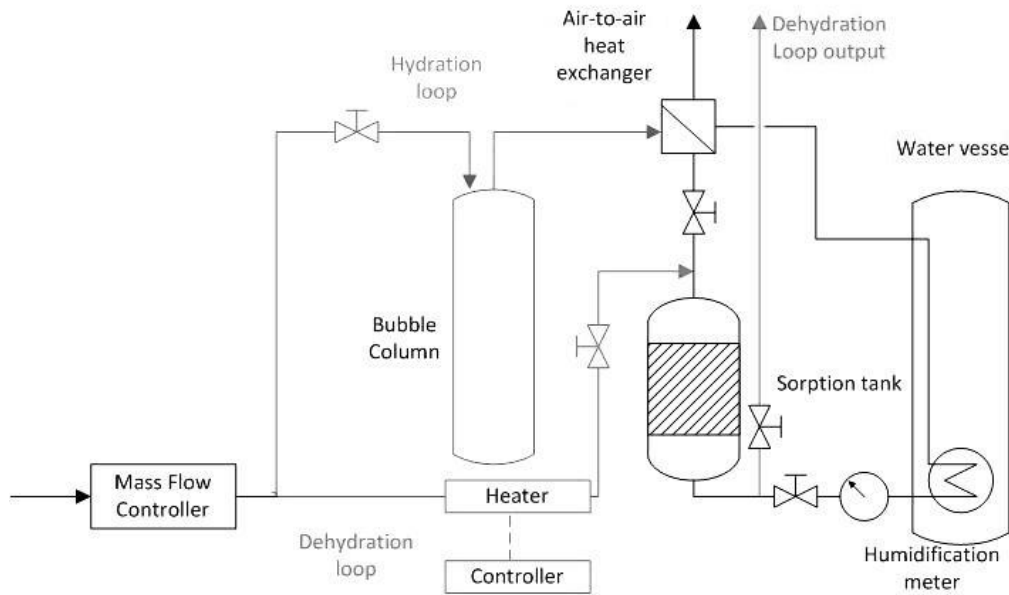


Figure (2): a schematic view of the setup

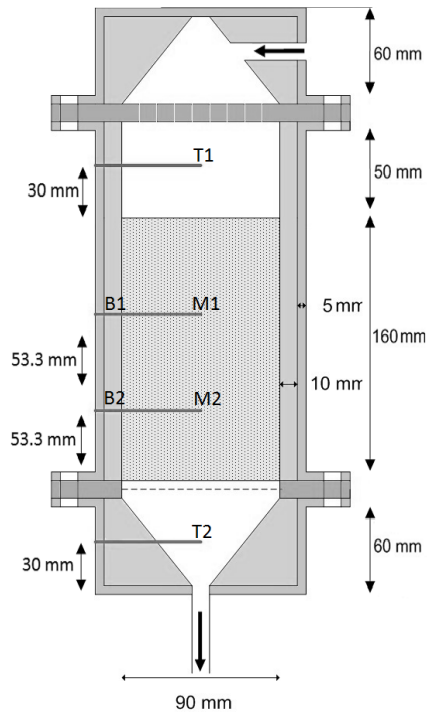
Table(1): Properties of the used materials in the reactor body

	Thickness (mm)	Thermal conductivity (W/m.K)
PTFE (Teflon)	10	0.35-0.45
Armaflex HT (Foamed EPDM Rubber)	25	0.038-0.042

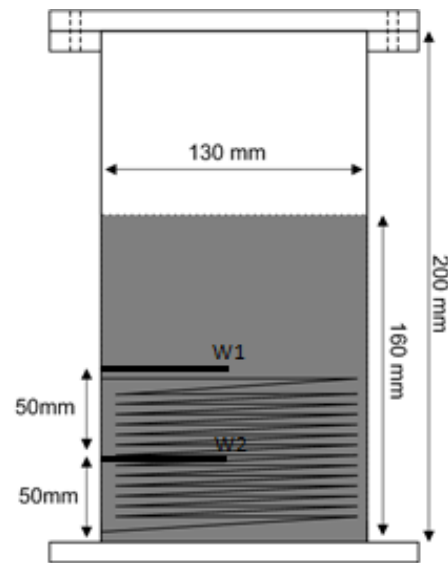
The positions of the six thermocouples attached to the reactor are shown in Figure(3). T1 and T2 measure the inlet and outlet temperatures, respectively, M1 and M2 measure the temperature of the bed at different heights. B1 and B2 are attached to the body of the reactor at the inside wall. The temperature and humidity of the outflow are measured. The water content in the outflow of the reactor can be monitored by a humidity-temperature sensor located at the outlet. In combination of the measured temperature and relative humidity, the water content in the outflow can be calculated.

An Internal heat exchanger is installed in the water vessel in order to transfer the heat from the hot outflow of the reactor to the water during the hydration experiment. It is a helical coiled pipe with length of 1.5 m and with UA-value of 5 W/K. Two thermocouples (W1 and W2) are installed in different heights of the water vessel in order to monitor the water temperature and the stratification effect. A25 mm layer of Armaflex AT insulation with thermal conductivity of 0.035 W/(m·K) is used around the water vessel which results a total heat loss UA-value of 0.1315 W/K for the water vessel. The dimensions of the water vessel and the positions of the thermocouples are shown in Figure(4).

An air-to-air heat exchanger is installed in the setup to implement the heat recovery during the hydration. The outflow air of the water vessel heat exchanger is used as the hot stream to preheat the inflow air of the reactor. A cross flow plate-fin heat exchanger with thin aluminum sheets is used. The fins between the sheets increase the heat transfer area.



Figure(3): a schematic view of the reactor



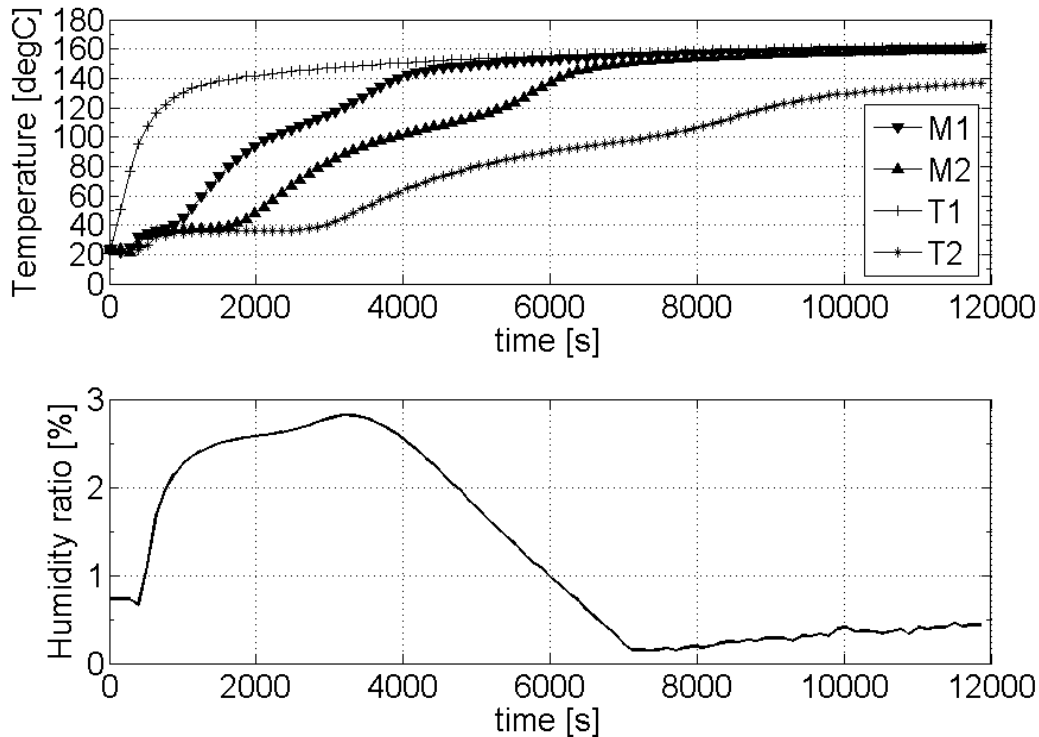
Figure(4): water vessel and positions of thermocouples

4. Results and discussion

The dehydration and hydration experiments of zeolite 13X are done in the setup and the results are presented here. The applied air flow rates in the experiments are 70 lit/min and the ambient temperature is around 25 °C. In this condition and during the hydration experiment, the bubble column becomes stable after 1 hour and humidifies the air flow up to 84% relative humidity at a temperature of 15 °C; therefore the humidity ratio is calculated to be 8.7 gram of water per kilogram of dry air which is in the range of a borehole system (7.6 gram of water per kilogram of dry air at a temperature of 10 °C). The temperature drop from 25 °C to 15 °C in the air flow through the bubble column is because of the water evaporation.

In the dehydration experiment, the temperature of the heater is set at 200 °C which leads to an increase in temperature from 25 °C to 160 °C at the inlet of the reactor (T1). The measured temperatures and humidity ratio (gram of water per 100 grams of dry air) in a dehydration experiment are shown in Figure(5). The temperature in the bed starts to increase layer by layer after the experiment is started. Two endothermic effects can be determined in the graph; one is around the bed temperature of 35 °C and the other one is around 120 °C. This may be related to the sorption characteristics of the zeolite, but to establish this, additional DTA measurements need to be done. After almost two hours the humidity ratio becomes zero which means that the material is dehydrated as far as possible with this dehydration temperature and vapor pressure. The remaining fluctuations in the humidity ratio are due to the limited accuracy of the humidity measurement at high temperatures, since the humidity ratio is calculated from the measured relative humidity.

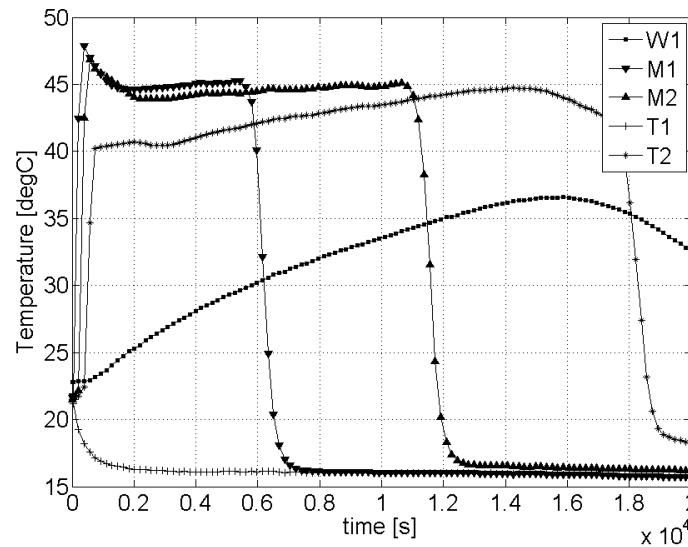
For hydration two experiments, one with and one without the air-to-air heat exchanger, are done and the results are presented in Figure(6) and Figure(7). The reactor is coupled to the water vessel in order to use the released energy from the reaction to warm up the water. Since the temperature of the water in the vessel is almost the same along the height, only one of the temperatures (W1) is shown in the figures.



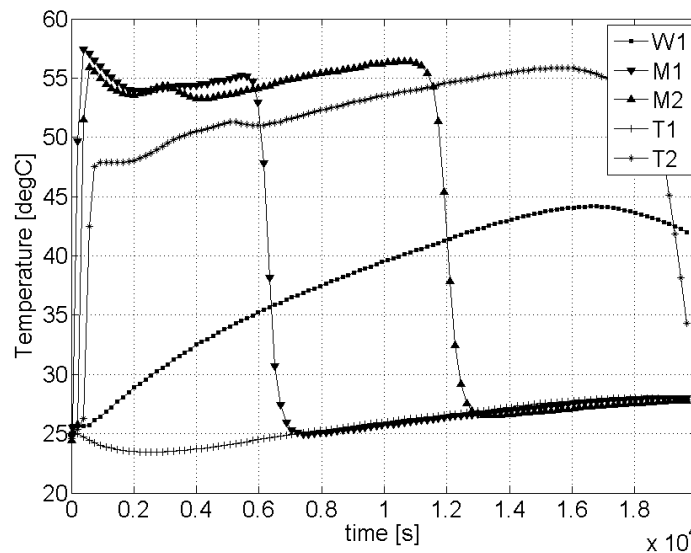
Figure(5): results of the dehydration experiment

In Figure(6) related to the hydration experiment without the air-to-air heat exchanger, it can be seen that the temperature at the top half of the bed (M1) rises quickly to more than 45 °C. Consequently the temperature at the bottom half of the bed (M2) increases because the produced heat is transferred by air flow through the reactor. The outflow temperature (T2) also increases suddenly after the experiment is started to the temperature of 40 °C which is somewhat lower than the bed temperature due to heat losses. The hot outflow warms up the water in the vessel which is reflected in the graph by the water temperature (W1) increase. After almost 1.5 and 3 hours, the temperature at M1 and M2 start to decrease which shows the reaction is finished in the top and bottom half of the reactor, respectively. The outflow temperature still increases until 4 hours after the start of the experiment due to the reaction in the last layers of the bed. After that for about 1 hour, the hot hydrated material in the bed losses its heat to the flow and keeps it at a high temperature. The water temperature (W1) starts to decrease when the outflow temperature starts to decrease which means the reaction is completely finished in the bed.

In Figure(7) related to the hydration experiment with the air-to-air heat exchanger, almost the same pattern can be seen and the reaction front can be determined at the same times in the bed. At the beginning of the experiment the inflow temperature (T1) decreases slightly for almost half an hour which is the required time for the bubble column equilibrium. After that the inlet temperature starts to increase because of the preheating effect in the air-to-air heat exchanger. It creates a higher temperature steps in the bed and outflow temperatures which are almost 10 °C. The maximum temperature achieved in the water vessel is also improved for about 8 °C by implementing the heat recovery. The maximum achieved temperature in the system is about 56 °C; however the highest water temperature is about 44 °C. Therefore the performance of the heat exchangers in the system needs to be improved. Specially the air-to-air heat exchanger effectiveness is low, since the temperature of the hot air stream is about 44 °C at the highest, but the reactor inflow is only preheated up to 28 °C.



Figure(6): results of the hydration experiment without the air-to-air heat exchanger



Figure(7): results of the hydration experiment with the air-to-air heat exchanger

5. Conclusion

A test setup is designed and tested to simulate the thermo-chemical long term heat storage, in order to investigate the applicability of the system for providing hot tap water in the built environment. Performance of the system is examined in hydration and dehydration experiments. In hydration, the released energy in the reactor is transferred by the air flow to the water vessel to warm up water. The performance of the system is improved by an air-to-air heat exchanger for implementing the heat recovery; the remaining heat in the air flow after the water vessel is used to preheat the inflow of the reactor. The maximum achieved temperatures in the water vessel are about 36 and 44 °C for hydration without and with the heat recovery, respectively. Since the required temperature for hot tap water is 65 °C, the performance of the system needs a great improvement, specially regards to the air-to-water and air-to-air heat exchangers. In addition, making the system compact and well insulated is important.



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