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Research Paper

Investigation of a household-scale open sorption energy storage system based on the zeolite 13X/water reacting pair

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A B S T R A C T

Sorption thermal energy storage is a promising concept for seasonal heat storage. Advantages of sorption heat storage are high energy storage density (compared to sensible and phase change heat storage) and negligible energy losses during storage over long time periods. In order to investigate the potential of sorption thermal energy storage, a high power open sorption heat storage system has been designed and built for household space heating applications. In this paper, the characteristics of the open zeolite 13X/water sorption energy storage system will be presented. The setup consists of four segments with a total capacity of 250 L of zeolite. A segmented reactor has been designed to reduce the pressure drop over the system, which results in less required fan power. This configuration also decreases the response time and makes the system scalable. Dehydration of the reactor is performed by supplying hot air to the zeolite bed. Hydration is performed by supplying humidified air to the bed. In all the segments, the pressure drop, temperature, and humidity are monitored. Furthermore, inside one of the reactor segments, the temperature is monitored at different locations in the zeolite bed. Several tests, using different mass flow rates, have been performed. During the tests, a maximum temperature step of 24 °C was realized. The maximum delivered power was 4.4 kW and the obtained storage capacity was 52 kWh. The reactor efficiency was 76% taking into consideration the conductive heat losses through the reactor wall and the sensible heat taken up by the thermal mass of the solids. Furthermore, it has been noticed that the flow through the bed was not completely uniform. This has a negative influence on the performance of the system.

1. Introduction

Currently, the energy sector is undergoing a transition towards a more sustainable future. The use of fossil fuels is slowly phased out and more energy is produced by renewable energy sources. A promising renewable energy production technology is solar thermal, especially since heating accounts for 64% of the total energy consumption in Dutch households [1]. However, there is a seasonal mismatch between supply and demand regarding to solar thermal energy. During summer, solar energy is abundant but the demand for heating is low, while in winter the demand is high but the supply is low. This mismatch between supply and demand could potentially be resolved by seasonal thermal energy storage.

A promising method to store heat is by using sorption energy storage. This method allows for almost loss-free heat storage for a long time period [2,3,4]. The principle of sorption energy storage is based on a reversible interactions between the sorbate and sorbent according to $A(s) + B(g) \leftrightarrow AB(s) + heat$. During the endothermic charging process, heat is added to the sorption material, breaking the bonds of the sorbate to the sorbent, storing heat. At a later time, the stored heat can be retrieved by combining the sorbent and sorbate together (discharging). Here, the sorbent (A) is zeolite 13X and the sorbate (B) is water vapor. Zeolite is a good candidate to be used in reactor studies because of its high stability [5]. Since heat is not stored in a temperature difference between the material and the environment, but rather in the chemical bonds between sorbate and sorbent, there are no significant energy losses over long time periods.

In the past decade, lab or pilot setups have been developed and tested, attempting to integrate thermochemical heat storage in an overall system. Most of the systems utilize a packed-bed configuration. A disadvantage of the packed bed reactor design is the risk of formation of non-reactive zones, leading to a lower energy storage density. Table 1 shows open systems using zeolite as storage material.

Johannes et al. [6] realized a high power open sorption heat storage system (STAID), which contains two reactor segments, each containing 40 kg of zeolite 13X. The system is to be integrated in a domestic

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Nomenclature

Roman letters

A	cross section area [m^2]
b	isotherm model affinity constant [–]
c_p	specific heat capacity at constant pressure [kJ/(kg·K)]
ΔE	activation energy of desorption [J/mol]
h	adsorption enthalpy [kJ/mol]
$LFDI$	local velocity deviation index [–]
M	molar mass [kg/mol]
$\dot{m}$	mass flow rate [kg/s]
n	isothermal model exponent constant [–]
P	power [kW]
p	pressure [Pa]
Q	thermal energy [kJ]
q	zeolite water loading [mol/kg]
R	gas constant [J/(K·mol)]
t	time [s]
T	temperature [K]
	velocity [m/s]
V	volume [m^3]
x	absolute humidity [kg/kg]

Greek letters

α	isothermal model parameter
η	efficiency [–]
ρ	density [kg/m^3]

Subscripts

eq	equilibrium
rf	reaction front
th	theoretical

ventilation system, and provide space heating during peak hours. The hydration temperature was kept at 20 °C with a sorbate vapor pressure of approximately 16.3–15.8 mbar. Running the segments in parallel, the system is able to supply a maximum thermal power output of 2.25 kW during 6 h, with a maximum COP of 6.8. The power output is constant for 6 h during the discharge phase. However, following this constant power period, the power output decreased during 4 h to the point where the material is fully discharged. A maximum outlet temperature of 57 °C was achieved.

In order to avoid the formation of non-reactive zones Zettl et al. [7] of the Austria Solar Innovation Center (ASIC) developed a rotating drum reactor filled with 50 kg zeolite 4 A or zeolite X. This method is expensive and requires extra mechanical energy to revolve the reactor. At a hydration temperature of 25 °C, the applied sorbate water vapor pressure was 25 mbar. The system is able to deliver a maximum thermal power of 1.5 kW with a maximum COP of 12, taking into account the electrical power to operate the process. The maximum outlet temperature of the system is 60 °C.

The E-HUB/ECN developed a prototype using two packed bed modules, totaling 150 kg zeolite 13X [8]. The aim is a compact long-term heat storage solution for low-energy single family houses. An air-to-air heat recovery unit was installed to increase the inlet temperature up to 40 °C using residual heat in the outflow, which allows for higher outlet temperatures. The air flow to the zeolite bed is humidified to 12 mbar water vapor pressure. The maximum delivered power is 0.4 kW, and the maximum outlet temperature of the system is 70 °C.

The MONOSORP prototype is developed as an open heat storage system for space heating in the built environment [10]. The storage material is zeolite 13X and the system contains honeycomb structures instead of ordinarily employment fills. These structures have a large number of small straight channels that ensure a low pressure loss. The hydration temperature is approximately 20 °C and the applied water vapor pressure is 12 mbar. The maximum outlet temperature is approximately 42 °C. The system delivers a maximum power output of 1.5 kW.

Michel et al. [9] developed a large scale prototype using 400 kg of $SrBr_2$ packed in eight separate modules on top of each other. Each module has a reactive bed with a thickness of 7.5 cm and a diffuser with a thickness of 1.5 cm. In order to maximize the reactor energy storage density, the number of modules and diffusers should be minimized by using thicker reactive beds. However, a larger thickness limits mass transfer and reduces the thermal power output. This indicates that there is an optimum value in terms of reactive bed thickness. Gaeini et al. determined the optimal aspect ratio of the reactive bed [11]. This aspect ratio is implemented in the design of the pilot reactor of this work.

In this work, the design of a sorption storage system is presented, taking into account the issues reported in literature. The developed pilot reactor has several key characteristics to achieve a high-power, flexible system:

- The reactor segments have an optimum aspect ratio, which maximizes the efficiency and minimizes the pressure drop [11].
- The system is modular, which allows for easy upscaling.
- The segmented approach of the system reduces the pressure drop over the reactor vessels and decreases the sensible heat loss, therefore increasing the efficiency.
- The first reactor segment is equipped with additional thermocouples to investigate the formation of non-reactive zones.

The developed sorption energy storage system can be used to store heat for domestic applications. The main prospect of this technology is heat storage for domestic applications. It can provide temperatures suitable for space heating and with the addition of a heat recovery unit, temperature suitable for hot tap water. Experiments have been performed to demonstrate the power and capacity of the setup, and to investigate the non-reactive zones in the reactor bed. The developed pilot setup is in terms of energy density and sorption temperature is mapped in Fig. 1, together with the previously described zeolite prototypes of Table 1.

Table 1
Open system prototypes along with operating conditions.

Project name	Year	Material	T_{charge} [°C]	$T_{discharge}$ [°C]	Energy density [kWh/m^3]	Max power [kW]
STAID [6]	2015	80 kg zeolite 13X	120–180	20	114	2.25
ASIC [7]	2014	50 kg zeolite 4A/X	230–180	25	148	1.5
E-HUB/ECN [8]	2014	150 kg zeolite 13X	185	25–60	58	0.4
PROMES-CNRS [9]	2014	400 kg $SrBr_2$	80	25	203	0.8
MONOSORP [10]	2006	70 kg zeolite 4A	170	20	120	1.5