Applied Energy 129 (2014) 177–186

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Experimental investigation of an innovative thermochemical process operating with a hydrate salt and moist air for thermal storage of solar energy: Global performance

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HIGHLIGHTS

- A large scale thermochemical storage system working with moist air is experimented.
- High energy density (203 kW h/m^3) and storage capacity (105 kW h) have been obtained.
- Hydration specific powers between 0.75 and 2 W/kg have been reached.
- The ways to control the storage system have been deeply investigated.
- Two important parameters (equilibrium drop and mass flowrate) have been identified.

ARTICLE INFO

Article history:
Received 23 December 2013
Received in revised form 25 March 2014
Accepted 22 April 2014
Available online 23 May 2014

Keywords:
Thermochemical process
Open sorption process
Solid–gas reaction
Thermal storage
Seasonal storage
Solar energy

ABSTRACT

This paper investigates an innovative open thermochemical system dedicated to high density and long term (seasonal) storage purposes. It involves a hydrate/water reactive pair and operates with moist air. This work focuses on the design of and experimentation with a large scale prototype using $SrBr_2/H_2O$ as a reactive pair (400 kg of hydrated salt, 105 kW h of storage capacity and a reactor energy density of 203 kW h/m^3). Promising conclusions have been obtained regarding the feasibility and performance of such a storage process. Hydration specific powers from 0.75 to 2 W/kg have been reached for a bed salt energy density of 388 kW h/m^3. Moreover, two important parameters that control the storage system have been identified and investigated: the equilibrium drop and the mass flow rate of moist air. Both have a strong influence on the reaction kinetics and therefore on the reactor's thermal power.

1. Introduction

The energy demand for buildings accounts for 25% of total energy consumption in the world and 40% in Europe. Space heating represents the main part of this energy: 53% in the world and about 80% in Europe [1]. The increasing scarcity and cost of fossil fuels and incentives to reduce greenhouse gas emissions have led to a growing interest in solar energy. Solar energy is widely affordable and has the capability to meet household demand over the year. Unfortunately, its intermittency and variability with weather conditions, time, and seasons lead to a mismatch between heating demand and solar energy availability.

Thus, a key issue to maximize the use of solar energy for space heating is to valorize the excess solar energy in summer by implementing long-term storage (3–6 months). Such a seasonal storage system must have the lowest heat losses between summer and winter, and the highest energy density to reduce its size and cost.

Several studies have dealt with seasonal storage for residential applications [2,3]. Among available storage systems, a sorption process takes advantage of a high storage density (about 100–500 kW h/m^3 of storage material), and weak heat losses between the storage and heating periods because the energy is stored as chemical potential and the sensible heat is weak. Therefore, such a system is relevant for seasonal storage for space heating for households. In comparison with competitive systems, the energy density is about 90 kW h/m^3 for latent storage and about 54 kW h/m^3 for water (sensible heat over $\Delta T = 70\,^{\circ}C$ and 25% heat losses) [4].

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http://dx.doi.org/10.1016/j.apenergy.2014.04.073

Nomenclature

A	affinity, J/mol$_s$
c_m	heat capacity, J kg^{-1} K^{-1}
Dec	energy density of the reactive bed, J m^{-3}
Der	energy density of the reactor, J m^{-3}
G	reactive gas
HR	relative humidity
K	equilibrium constant
k	permeability, m^2
M	molar weight, kg mol^{-1}
m	mass, kg
$\dot{m}$	mass flow rate, kg s^{-1}
N	mole quantity of salt, mol
p	pressure, Pa
Δp	pressure drop across the salt bed, Pa
$\dot{Q}$	reaction power, W
$\dot{Q}_m$	specific power, W/kg
S	reactive solid
R	gas constant, J mol^{-1} K^{-1}
T	temperature, K
T'	temperature, °C
$\dot{V}$	flow rate, m^3/h
w	specific humidity, kg$_v$ kg$_a^{-1}$
X	reaction advancement

Greek symbols

Δh_r^0	standard enthalpy of reaction, J mol$_s^{-1}$
ΔS_r^0	standard entropy of reaction, J mol$_s^{-1}$ K^{-1}
λ	thermal conductivity, W m^{-1} K^{-1}
ν	stoichiometric coefficient, mol$_G$/mol$_s$
ΔX	advancement variation

Indices

0	dehydrated salt
1	hydrated salt
a	dry air
amb	ambient
$eqLG$	liquid/gas equilibrium
$eqSG$	solid/gas equilibrium
h	moist air
i	inlet of the porous bed
j	outlet of the porous bed
r	reaction
s	salt
t	total
v	water vapor
X	reaction advancement

Exponent

0	reference

Sorption processes are increasingly being investigated for storage purposes, either regarding reactive materials or the workings of the storage system [3]. Several prototypes of sorption storage have been experimented with [5–19] at a small scale; the largest is the SOLUX system, which stores 60 kW h [7]. Nevertheless, no large-scale seasonal project has yet been completed [20].

Let's recall that different energy densities can be defined for these systems, referring to volumes of active material only, or to the whole reactor implementing the active material and including dead volumes and volumes dedicated to heat and mass transfer within the reactor and the coolant loops (heat exchanger, gas diffuser, collector, etc.). Fig. 1 compares these two energy densities for most of the prototypes, referring to the reactive material (x-axis) and the whole reactor prototype volume (y-axis).

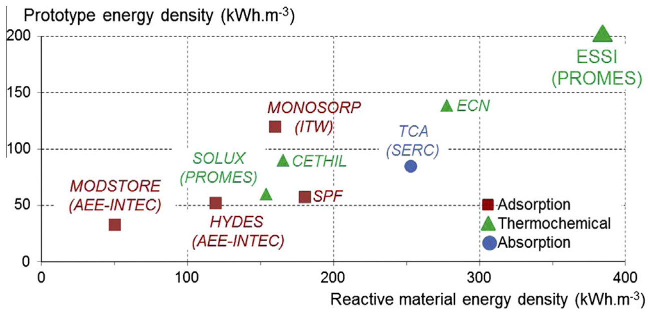

Fig. 1. Energy densities of various sorption storage prototypes as function of the energy density of the reactive materials implemented in the prototype: TCA (LiBr/H_2O, [10]), HYDES and MODSTORE (Silica gel/H_2O, [12,13]), SPF (Zeolithe 13X/H_2O, [19]), MONOSORP (Zeolithe 4A/H_2O, [14]), CETHIL ($MgSO_4$ + Zeolithe 13X/H_2O, [18]), SOLUX ($SrBr_2/H_2O$, [7]), ECN ($MgCl_2/H_2O$, [8]), and ESSI: the prototype reported in this paper ($SrBr_2/H_2O$).

The energy density of the prototypes is significantly less than the reactive material energy density, i.e. only about half.

Among all these experiments, the highest values of the material and prototype energy densities are, respectively, 280 kW h/m^3 for the reactive material and 140 kW h/m^3 for the storage system. The work described in this paper aims at developing a solid/gas sorption storage system beyond this range and experimenting with it on a significant scale (about 1/10 the capacity of a long term storage system for house heating).

This thermochemical storage process involves a reversible chemical reaction between a solid and a gas (Eq. (1)). The reaction is a hydration/dehydration and a well-known hydrate/water pair has been selected (Eq. (2)). The synthesis (or hydration) of the solid is exothermic (destorage step), while its decomposition (or dehydration) requires heat input (storage step). A thermochemical process based on such a hydrate/water pair can operate according to two different modes: the salt can react with pure water vapor at low pressure or with a moist air flow at atmospheric pressure. The first working mode is standard and simple, and most thermochemical systems in the literature operate with pure water vapor [6,7,12,16,17]. Nevertheless, this low pressure generates strong technological constraints for the reactor. On the other hand, the innovative operating mode with moist air allows a less expensive reactor conception [21] but its management is more complex. Only a few authors are currently investigating the feasibility and performances of systems running with moist air [8,15,22–25]. So far, the successful operation of a seasonal storage system based on a thermochemical process operating with moist air has never been demonstrated at the pilot-scale. This challenge is the reason for this study.

Therefore, a prototype thermochemical storage reactor operating with moist air has been designed and experimented. Several previous works and literature reports outlined the background of this study. They are summarized in the following: