

Experimental investigation of an open thermochemical process operating with a hydrate salt for thermal storage of solar energy: Local reactive bed evolution



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HIGHLIGHTS

- Local behavior of open thermochemical storage systems using packed bed is studied.
- The mass transfer evolution within the reactive bed is carefully investigated.
- An asymmetric evolution of the bed permeability have been highlighted during reaction.

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ABSTRACT

Their high energy density and low heat losses between storage and recovery times make thermochemical processes a promising way to achieve long-term (seasonal) storage. Among the available reactor configurations, open systems using a packed bed of reactive solid are simple and efficient. This paper reports on the local operation and reactive bed behavior of such systems. Mass transfer changes within the reactive bed, which is the main limitation of such systems, was investigated using several state variables (reaction advancement, pressure drop across the salt bed and bed temperatures). Results from two experimental set-ups were analyzed: a small bench for mass transfer characterization, and a prototype at a larger scale. Both used SrBr₂/H₂O as reactive pair.

A salt bed temperature analysis evidenced a reaction front moving within the reactive layer from the moist air inlet to its outlet. A mass transfer study showed marked changes in the reactive bed permeability during the reaction (by one order of magnitude) and with the reactive bed density (from 10⁻⁹ to 10⁻¹² m² when density range from 300 to 600 kW h m⁻³). During the reaction an asymmetric time course of the bed permeability was also highlighted: as $f(X)$ in dehydration and $f(1/X)$ in hydration.

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1. Introduction

Energy demand for buildings accounts for 25% of total energy consumption worldwide and 40% in Europe. Most of this energy is used for space heating: 53% worldwide 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 ways to reduce energy consumption, in particular in the residential sector. The use of renewable energies, and in particular solar energy for household applications, is one major way to decrease energy consumption and greenhouse gas emissions in the residential sector generally. Unfortunately, the solar resource is intermit-

tent, and there is a mismatch between the supply and demand periods. Accordingly, to optimize the use of solar energy, especially for house heating, it would be useful to be able to conserve excess solar energy delivered in summer by long-term thermal storage (3–6 months).

Interest in seasonal storage for residential applications is currently rising, and several studies have been carried out [2–5]. Such storage systems must lose as little heat as possible between summer and winter, and be as compact as possible i.e. have the highest possible energy density. Among available processes, thermochemical storage is regarded as the solution with the greatest long-term potential [3,6–9]. It offers the advantage of negligible heat losses between storage and recovery periods because the energy is stored as chemical potential, and the sensible heat of the elements is low. Moreover it offers a high storage density (about

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Nomenclature

Dec	salt bed energy density (J m ⁻³ or kW h m ⁻³)	μ	dynamic viscosity (kg m ⁻¹ s ⁻¹)
Der	reactor energy density (J m ⁻³ or kW h m ⁻³)	ν	stoichiometric coefficient (mol _G mol _S ⁻¹)
G	reactive gas	ρ	density (kg m ⁻³)
HR	relative humidity (%)	Ω	bed cross section (m ²)
h	high (m)		
k	permeability (m ²)	Indices	
L	width (m)	0	dehydrated salt
l	length (m)	1	hydrated salt
M	molar weight (kg ⁻¹ mol ⁻¹)	a	dry air
m	mass (kg)	amb	ambient
p	pressure (Pa)	bed	reactive bed
Δp	pressure drop across the salt bed (Pa)	eq	equivalent
S	reactive solid	eqSG	solid/gas equilibrium
R	gas constant (J mol ⁻¹ K ⁻¹)	g	overall
T	temperature (K)	i	inlet
\dot{V}	flow rate (m ³ s ⁻¹)	j	outlet
w	specific humidity (g _v kg _a ⁻¹)	s	salt
X	reaction advancement	v	water vapor
Z_s	bed thickness (m)	X	at the reaction advancement X
		Exponent	
Greek symbol		0	reference
Δh_r^0	standard enthalpy of reaction (J mol _v ⁻¹)		
Δs_r^0	standard entropy of reaction (J mol _v ⁻¹ K ⁻¹)		

200–500 kW h m⁻³). In comparison, energy density is about 90 kW h m⁻³ for latent storage and about 54 kW h m⁻³ for sensible heat storage (water, $\Delta T = 70$ °C, heat losses of 25% [10]).

Thermochemical storage involves a reversible chemical reaction between a solid and a gas:

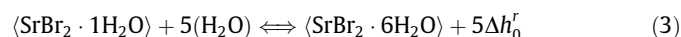


This thermochemical process is a monovariant system; the equilibrium conditions (p_{eqSG} , T_{eqSG}) of the solid/gas reaction follow the Clausius-Clapeyron relation (Eq. (2)). Thus assuming the reactive gas behaves as a perfect gas, we can write:

$$\ln\left(\frac{p_{eqSG}}{p^0}\right) = -\frac{\Delta h_r^0}{RT_{eqSG}} + \frac{\Delta s_r^0}{R} \quad (2)$$

where Δh_r^0 and Δs_r^0 are respectively the standard enthalpy and entropy of the solid/gas reaction (per mol of gas) and p^0 is the reference pressure (1 bar). The synthesis (or hydration) of the solid S_1 is exothermic (heating or heat recovery period); its decomposition (or dehydration) requires a heat input (storage period).

Numerous salt hydrates have been proposed in the literature for thermochemical storage [11–15]. The solid/gas pair studied in this paper is the hydrate/water pair strontium bromide/H₂O:



$\langle \text{SrBr}_2 \cdot 1\text{H}_2\text{O} \rangle$ and $\langle \text{SrBr}_2 \cdot 6\text{H}_2\text{O} \rangle$ are respectively the dehydrated (S_0) and hydrated (S_1) salts and the reactive gas (G) is water. Mauran et al. [16] measured the standard enthalpy and entropy of the reaction: $\Delta h_r^0 = 67,400$ J/mol_v and $\Delta s_r^0 = 175$ J/K/mol_v.

This reactive pair had already been found promising for low-temperature thermochemical processes for thermal storage and house-heating applications, especially using solar energy [8,9,13,16]. Its equilibrium conditions allow its dehydration with solar energy (temperature under 80 °C) and allows temperatures restitutions compatible with house heating (up to 30 °C) during hydration. Its ideal energy storage density is very high: 629 kW h m⁻³ (referring to its bulk density, 2390 kg m⁻³, and molar mass of hydrated salt, 0.3555 kg mol⁻¹) [17]. Note that the

energy density of the reactive bed (Dec) is defined by the following relation:

$$\text{Dec} = \frac{\rho_{bed} \cdot \nu \cdot \Delta h_r^0}{M_s} \quad (4)$$

A prior small-scale experiment [18] showed its suitability for seasonal storage applications. In particular, high reactive bed energy densities were reached (up to 400 kW h m⁻³ of reactive bed volume).

For thermochemical systems, the simplest and most efficient reactor configuration has to be defined in order to reduce manufacturing, operating and maintenance costs. Various solid/gas reactor configurations have been proposed in the literature [19–21], and three main technologies emerge: packed bed, moving bed (screw or rotary reactor, gravity assisted bulk flow, etc.) and fluidized reactor. A porous packed bed of reactive solid is generally considered to be the most appropriate reactor configuration for hydration/dehydration [21], and has been used in several thermochemical systems [8,22–24]. This simple, cheap reactor configuration was selected for this study.

Thermochemical reactors using a hydrate/water pair can operate in two different modes: closed or open. Both have been studied in the literature, both numerically and experimentally [21,25].

In closed thermochemical systems [8,22,24,26–28], the salt reacts with pure water vapor at fairly low pressure. This type of operation well below atmospheric pressure generates strong technological constraints for reactor design, and any leakage strongly reduces reactor performance [29]. This reactor configuration is therefore unsuitable for large-scale storage applications.

In an open system [5,18,30–36], the reactive solid bed is permeated by a moist air flow at atmospheric pressure, allowing simpler and cheaper reactor design. It also requires no evaporator/condenser or water tank, which increases compactness. The feasibility of open systems has been studied in recent research, and they seem promising for seasonal storage applications [37,38]. However, most of these studies have addressed overall performance of the storage process [5,34,36], and none addresses the local analysis of a thermochemical reactor for storage systems. Yet,

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