



Performance analysis of a thermochemical based heat storage as an addition to cogeneration systems



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ABSTRACT

A closed thermochemical heat storage system based on pure salt hydrate, namely $\text{SrBr}_2 \cdot 6\text{H}_2\text{O}$ is developed and its performance, numerically investigated. This paper focuses on system development as an addition to existing micro-combined heat and power (cogeneration). The originality of this work lies in the fact that it models the coupled heat and mass transfer with chemical reaction on a 3D geometry to be closed to reality. Besides, a reaction front model is also developed, in order to determine optimal parameters (bed porosity, bed thickness kinetic behaviour) and thermal power, required for system efficiency. Then, sensitivity of permeability and thermal conductivity on the reaction efficiency is numerically demonstrated, leading to some recommendations for future prototype development. Results exhibit a theoretical reactor energy storage density of 115 kWh m^{-3} , storage capacity of 61 kWh, thermal efficiency of 78% (at 90% of reaction conversion) and COP_{th} of 0.97, highlighting system performances. An average output temperature of $52 \text{ }^\circ\text{C}$ is numerically obtained. A comparison simulation-experiment is then performed and discussed, showing encouraging results, even if limited at lab-scale. Performances are quite similar, consolidating the idea that, waste heat from cogeneration can be re-used with 78% of efficiency.

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1. Introduction

Research on sustainable energetic systems is nowadays beyond theoretical knowledge and striving for commercial products though practical constraints remain to be solved. Whether controlling the flow of intermittent renewable energy or recovering heat from industrial discharges, energy storage appears as a promising method for the introduction of low carbon energy and energy efficiency. Heat recoveries in buildings (moving heat from one zone to another, integrated solutions), from existing systems (waste heat), from nature (solar, wind) are different means of replacing or saving fossil fuels in several years. Achieving that previous statement can be done through seasonal or long-term thermal energy storage. Energy storage is necessary today if you want to achieve greater energy efficiency and to use a large scale of renewable resource,

in particular for the long-term storage. Thermochemical energy storage systems play a key role in order to fulfil this objective through, among others, chemical heat pumps and heat storage processes [1]. Among the available storage systems [2,3], thermochemical systems that are chemical reaction and/or sorption phenomena, exhibit high storage density range ($0.5\text{--}3 \text{ GJ m}^{-3}$ of storage material at hydrated state), and small heat losses between the storage and heating periods because the energy is stored as chemical potential and the sensible heat is weak. Although it is a high performance system compared to latent and sensible storage [4], the technology is relatively immature and not yet commercialized.

From varied applications of thermochemical systems (heat pumps, air conditioning, heating and cooling), waste heat recovery such as from combined heat and power (CHP) is the main interest within this work. The difficulty to transfer useful heat over long distances is a serious constraint, which may limit the use of simultaneous generation of CHP when the heat load is highly variable or limited to excessively short time intervals. This is, for instance, the case of space heating in many buildings in the tertiary sector, where the heating load is limited to the daily time on working days. In a thermal load following operation, time variation would

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Nomenclature

a	honeycomb cell size (m)	t'_α	dehydration time (s)
A, A_0	area, heat exchanger area (m^2)	t_α	hydration time (s)
A_f	frequency factor of Arrhenius (s^{-1})	\mathbf{u}	velocity vector (m s^{-1})
C_0	initial concentration of salt hydrate (mol m^{-3})	\mathbf{u}_v	vapour (steam) velocity vector (m s^{-1})
C_f	final concentration of the salt hydrate (mol m^{-3})	V_f	volume flow rate of the vapour ($\text{m}^{-3} \text{s}^{-1}$)
C	concentration of the salt hydrate (mol m^{-3})	x, y, z	spatial coordinates (also representing thickness and width) (m)
C_p	specific heat capacity ($\text{J kg}^{-1} \text{K}^{-1}$)		
D_v	effective gas diffusivity in solid ($\text{m}^2 \text{s}^{-1}$)		
E_a	activation energy (J mol^{-1})	Greek symbols	
E_d	storage energy density of the salt (J m^{-3})	α	reaction conversion or advancement (%) or (-)
E_{dm}	mass storage energy density of the salt (J kg^{-1})	β	heating rate (K s^{-1})
$f(\alpha)$	function describing the influence of conversion, independently of temperature (-)	ρ	volumetric density (kg m^{-3})
g	acceleration of the gravity ($\text{m}^2 \text{s}^{-1}$)	μ	dynamic viscosity (Pa s)
$h(p)$	function describing the pressure effect during the chemical process	σ	energy ratio between the sensible and the reaction energy (%)
ΔH_r^0	standard enthalpy of reaction ($\text{J mol}^{-1} \text{K}^{-1}$)	ε	total porosity of the material bed (-)
\mathbf{j}	vapour mass flux ($\text{kg m}^{-2} \text{s}^{-1}$)	η	thermal efficiency (-)
$k(T)$	kinetic rate constant (s^{-1})	λ	thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)
k	permeability (m^2)		
m	mass of salt hydrate (kg)	Subscripts	
M	molar mass (g mol^{-1})	Al	Aluminium
\dot{m}	mass flow rate (kg s^{-1})	b, bed	salt bed
m_0	initial mass of salt hydrate (kg)	ch	charging
m_f	final mass salt hydrate (kg)	$cond$	condenser
N	steam molar flux ($\text{mol m}^{-3} \text{s}^{-1}$)	dis	discharging
\vec{n}	normal vector to a surface	ext	external to the material bed
p	vapour pressure (Pa)	$evap$	evaporator
P_{aver}	average thermal power during hydration (W)	eq, eql	equilibrium, equivalent
P_{aver_sht}	average thermal power during hydration based on sorption heat (W)	f	final, front (reaction)
P_{aver_v}	volumetric average thermal power during hydration (W)	g	gas phase
p_f	reaction front pressure (Pa)	h	convective heat transfer coefficient
P_{stored}	average thermal power during dehydration (W)	htf	heat transfer fluid
P_{stored_sht}	average thermal power during dehydration based on sorption heat (W)	HX	heat exchanger
P_{stored_1}	average thermal power during dehydration based on salt energy density (W)	$i, initial$	initial, starting condition
\dot{q}	volume power source (W m^{-3})	$inlet$	inlet, entrance
\mathcal{R}	ideal gas constant ($\text{J mol}^{-1} \text{K}^{-1}$)	$outlet, o$	outlet, output
R_{kin}	kinetic factor (s^{-1})	r	reaction
T	temperature (K)	s	salt
T_p	peak temperature usually obtained in thermal analysis experiment (K)	s_salt	sensible heat of the salt
t	time (s)	s_Al	sensible heat of the Aluminium part
		$s1$	salt in hydrated form
		$s0$	salt in dehydrated form
		$stored$	stored energy or power
		t, th	thermal
		v	water vapour, steam

cause the CHP unit to be switched on and off very frequently. Therefore, a transient behaviour is generated that may have a negative effect on both energy efficiency and system lifetime. While in an electric power following same way, time variation of the heating load may cause an excessive amount of waste heat, resulting in a decrease of the energy saving. Because of the difficulty to match the generated heat with the existing requirements, cogeneration systems (CHP) may operate efficiently if the production of electricity and heat are uncoupled by adding a thermochemical energy storage facility where heat that is not needed during the production period can be stored or directly used to drive the process (as demonstrated by Xu et al. [5]).

Several researchers on this subject, focused on heating for buildings using solar source [1,6–9] at low temperature, with few works dedicated to waste heat recovery [10,11]. Most of their

work, used $\text{SrBr}_2 \cdot 6\text{H}_2\text{O}$ as the reactive or storage material. Selection of this material was demonstrated as a suitable one for closed system at low temperature in a previous work [12], where the present operating conditions (T, p) are presented. Additionally, waste heats from CHP are estimated between 9% and 13% [13] corresponding to a temperature range of 95–115 °C, suitable for closed thermochemical systems at low temperature.

This paper concerns solid–gas thermochemical reactor operating in the so-called closed mode [14]. In classical thermochemical cycle, reactor is fed with water vapour (the reactive gas) produced by an evaporator, and, in a following phase, releases this vapour to a condenser (Fig. 1). The reaction heat is then exchanged through a heat exchanger, with a heat transfer fluid. Lahmidi et al. [6] firstly investigated a closed system based on composite ($\text{SrBr}_2 \cdot 6\text{H}_2\text{O}$ and graphite) for heating and cooling purpose using solar heat source.

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