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Energy density and storage capacity cost comparison of conceptual solid and liquid sorption seasonal heat storage systems for low-temperature space heating

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ABSTRACT

Sorption heat storage can potentially store thermal energy for long time periods with a higher energy density compared to conventional storage technologies. A performance comparison in terms of energy density and storage capacity costs of different sorption system concepts used for seasonal heat storage is carried out. The reference scenario for the analysis consisted of satisfying the yearly heating demand of a passive house. Three salt hydrates ($MgCl_2$, Na_2S, and $SrBr_2$), one adsorbent (zeolite 13X) and one ideal composite based on $CaCl_2$, are used as active materials in solid sorption systems. One liquid sorption system based on $NaOH$ is also considered in this analysis. The focus is on open solid sorption systems, which are compared with closed sorption systems and with the liquid sorption system. The main results show that, for the assumed reactor layouts, the closed solid sorption systems are generally more expensive compared to open systems. The use of the ideal composite represented a good compromise between energy density and storage capacity costs, assuming a sufficient hydrothermal stability. The ideal liquid system resulted more affordable in terms of reactor and active material costs but less compact compared to the systems based on the pure adsorbent and certain salt hydrates. Among the main conclusions, this analysis shows that the costs for the investigated ideal systems based on sorption reactions, even considering only the active material and the reactor material costs, are relatively high compared to the acceptable storage capacity costs defined for different users. However, acceptable storage capacity costs reflect the present market condition, and they can sensibly increase or decrease in a relatively short period due to for e.g. the variation of fossil fuels prices. Therefore, in the upcoming future, systems like the ones investigated in this work can become more competitive in the energy sector.

1. Introduction

Energy storage is one of the possible solutions for matching energy supply and demand in the future energy grid, in which intermittent and distributed energy production technologies will play an increasingly important role. In particular, energy storage is useful to increase the grid flexibility and safety, increase the amount of renewable energy sources, and improve the overall performance of energy systems [1].

Beside the previously mentioned benefits, and considering that the final energy use in domestic buildings is dominated by thermal energy (Fig. 1-1, bottom), thermal energy storage, or heat storage, can play a major role in reducing the primary energy consumption in buildings and in the future energy grid [2]. This is possible for example by decoupling the energy supply and demand sides, enabling the possibility to generate energy when it is more efficient and convenient, and store is till the time it is needed by the consumer.

Thermal energy storage can be divided into three main categories according to the storage mechanism: sensible, latent, and sorption heat storage. Sensible heat storage makes use of the temperature difference applied to a medium to store energy (e.g. water tank); latent heat storage exploits the phase change enthalpy of the medium, and sorption heat storage makes use of the reaction enthalpy involved in a typically reversible reaction.

The main advantages and drawbacks of the different technologies have been summarized in Table 1-1. Sensible storage is the most used and developed type of heat storage. For example, borehole heat storage

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Nomenclature

Symbol description unit

$\dot{Q}$	Thermal power W
$\dot{m}$	Mass flow kg/s
A	Area m^2
b	Langmuir-Freundlich isotherm parameter 1/Pa
b_0	Langmuir-Freundlich isotherm parameter 1/Pa
C	Cost €
ESH	Yearly energy for space heating GJ
c_p	Specific heat capacity J/(kg·K)
D_p	Particle diameter mm
E	Volumetric energy density GJ/m^3
e	Specific energy density kJ/kg
G	Gibbs free energy kJ
H	Enthalpy kJ
h	Specific enthalpy kJ/kg
L	Length m
M	Molar mass g/mol
m	relative mass, Dimensionless
n	Langmuir-Freundlich isotherm parameter, Dimensionless
n_1	Langmuir-Freundlich isotherm parameter, Dimensionless
n_2	Langmuir-Freundlich isotherm parameter K
p	Pressure mbar
P	Power kW
q	molar concentration mol/kg
R	Ideal gas constant J/(mol·K)
R_{cryst}	Ratio of crystallization, Dimensionless

S	Entropy J/(kg·K)
T	Temperature °C
V	Volume m^3
W	Weight t
x	Relative mass concentration, Dimensionless
ε	Porosity, Dimensionless
η	Efficiency, Dimensionless
μ	Viscosity Pa·s
ρ	Density kg/m^3

Abbreviations

ANF	Annuity Factor
DHW	Domestic hot water
ENG	Expanded natural graphite
HCT	High concentration tank
HR	Heat recovery
LCT	Low concentration tank
REC	Reference energy cost
SCC	Storage capacity cost
ST	Sorbate tank

Subscripts and superscripts

cap	installed capacity
eq	Equilibrium
M	material
sol	solution
vap	Vapor

is able to store large amounts of energy over the year for space heating, but large volumes of storage material (water and soil) are required [3]. Latent heat storage has a higher energy density over a small temperature range. However, the materials cost is typically higher, and certain materials have corrosion and stability issues. Pielichowska et al. [4] give an overview of the present state of the art of phase change materials (PCMs) for thermal energy storage applications while Sharif et al. [5] focus in particular on PCMs for space heating and domestic hot water (DHW) systems. Sorption heat storage has the highest theoretical energy density among the three categories of heat storage, and the heat losses can be, in principle, negligible. This, in turn, can result in a more compact system, which makes this technology prone to be used to store large quantities of energy over a relatively long period. Main drawbacks are the materials instability issues at the current state of research, and the low maturity level of the technology, which implies that its commercialization is not foreseen in the near future.

Sorption thermal energy storage uses physical and chemical bonds between at least two components, sorbent and sorbate, to store thermal energy. During the desorption phase, heat is added in order to separate the sorbent and the sorbate with an endothermic reaction. During the sorption phase, the two components are combined together and heat is released with an exothermic reaction (Fig. 1-1, top).

Different sorption materials are investigated for the purpose of thermal energy storage for long-term and low-temperature applications. In particular, pure adsorbents and salt hydrates are mainly investigated by the scientific community for the abovementioned applications [8–12]. Salt hydrates have theoretically high energy densities but hydrothermal stability issues make the use of these materials in their pure form challenging, especially in open systems. On the other hand, adsorbents are more hydrothermally stable but they have typically lower energy densities and higher costs. The research on composite materials aims to reduce the material instabilities by keeping acceptable energy densities and costs. Composites generally consist of at least two materials, in which one is the active material that
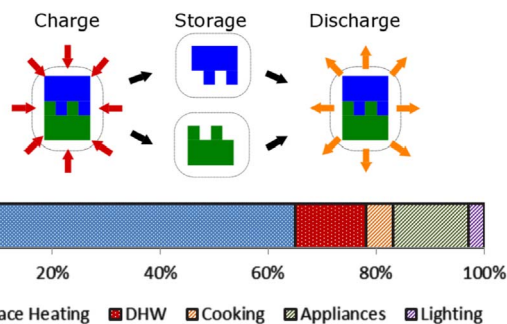

Fig. 1.1. Top: the sorption heat storage concept [6]. Bottom: End-use energy consumption of an household in EU (2012) [7]. Dotted bars: thermal energy; Striped bars: other forms of energy.

undergoes the sorption process and the other is mainly used for structural support. Beside the challenges at material-scale, at reactor- and system-scales, further issues such as heat and mass transfer through the reactor [13] and eventual components corrosion [14], have to be taken into account. Zondag [15] provides an introduction to sorption heat storage systems, with a particular emphasis on possible system configurations and overall system aspects. Abedin et al. [16] made a comparison among open and closed solid sorption systems based on energy and exergy analyses. The authors concluded that concerning charging, discharging and overall energy and exergy efficiencies, open systems were performing better than closed ones for the investigated cases. However, beside the thermodynamic factors, they suggested that other important factors such as economics have to be considered for the ultimate choice of a specific sorption heat storage system in a specific application. Hauer [17], discusses the possibilities and intrinsic limitations of sorption heat storage systems used for seasonal heat storage. Scapino et al. [18] gives an overview on the state of the art on sorption materials and existing sorption heat storage prototypes. Finally, Pinel et al. [19] and Xu et al. [20] provide an