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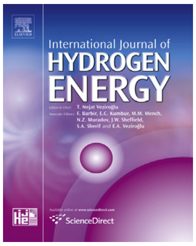

Metal hydride based thermal energy storage system requirements for high performance concentrating solar power plants

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ABSTRACT

High temperature concentrating solar power plants require suitable thermal energy storage systems to produce electric power efficiently. Thermochemical energy storage based on metal hydrides represents a very appealing prospect for low cost and high efficient solar storage systems. The objective of the paper is to assess the properties required by the metal hydride systems to achieve the U.S. Department of Energy's SunShot techno-economic targets. A simplified model has been developed to evaluate the cost and the exergetic efficiency of hydride-based storage systems. Results demonstrate that metal hydride materials, operating at temperatures higher than 650 °C, with reaction enthalpy on the order of 95–110 kJ/molH_2, raw material cost on the order of 1.4–2 \$/kg, weight capacities on the order of 3–4% and operating pressures on the order of tens of bars have the potential to closely approach the targets. Selected sensitivity analyses have also been carried out showing that the raw material cost, the material weight capacity and the metal hydride reaction enthalpy are the properties that strongly affect the performance of the storage system.

Introduction

Renewable source driven power plants are one of the most attractive options to produce electricity without local greenhouse gas emissions. Among these plants, CSP systems represent one of the most realistic options, mainly because it is possible to produce highly dispatchable electric power at high efficiencies and low costs [1,2]. However only CSP plants equipped with TES systems can compete economically with traditional fossil fuel plants to provide a stable energy resource that optimizes grid utilization [3–5]. Three types of TES systems are principally being developed today. They can store thermal energy as: (1) sensible heat (e.g. molten salts with no phase change), or (2) latent heat (i.e. phase change materials), or (3) thermochemical heat (i.e. through chemical reactions occurring in the materials).

Among the thermochemical systems, those using MH materials are unique, due to their high energy densities, reversibility and potential for low cost and high exergetic efficiency [6]. TES systems based on Li compounds were among the first MH systems investigated to store thermal energy at high temperatures. One application of Li-based TES systems integrated the TES with a solar parabolic concentrator plant for both solar power plants and for satellite

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Nomenclature

A	Heat transfer area, m^2
C_{HE}	Heat transfer system installed cost, $
C_M	Metal hydride material installed cost, $
C_{PV}	Pressure vessel (wall) cost, $
C_R	Cost of the raw metal hydride material, $
Cs	TES system specific cost, $/kWhth
CSP	Concentrating Solar Power
D_{in}	Heat transfer fluid tube diameter (Fig. 2), m
D_{out}	Single metal hydride structure diameter (Fig. 2), m
DOE	U.S. Department of Energy
DOF	Degree of freedom
D_{vessel}	Internal vessel diameter, m
Ech	Chemical exergy content, kJ
ENG	Expanded Natural Graphite
E_{th}	Thermal energy stored, kWhth
Eth	Thermal exergy content, kJ
h	Specific enthalpy, kJ/kg
HE	Heat exchanger
HTMH	High temperature metal hydride
k	Material thermal conductivity, W/m-K
L	Heat exchanger length, m
LTMH	Low temperature metal hydride
$\dot{m}$	Heat transfer fluid mass flow rate, kg/s
M	Metal hydride mass, kg
MH	Metal Hydride
M_{H2}	Mass of hydrogen to be stored in the metal hydrides, kg
n	Number of tubes of the heat exchanger
P	Pressure, bar
PCF	Plant Capacity Factor
PP	Power plant
PV	Pressure vessel
s	Entropy, kJ/kg-K
T	Temperature, K or °C
T_0	Reference temperature for exergy calculations, 298 K
TES	Thermal Energy Storage
U	Heat transfer coefficient, W/m^2-K
V	Metal hydride material volume, m^3
W_{el}	Average electric power produced by power plant during the year, MW
wf	Metal hydride weight capacity, kg_{H2}/kg_{MH}
W_{th}	Thermal power exchanged between the Metal Hydride and the heat transfer fluid, MW
x_{HE}	Heat exchanger and pressure vessel installation factor, accounting for installation costs
x_M	Metal hydride material installation factor, accounting for handling, modification and allocation of the metal hydride material

Greek letters

Δt_s	Storage time, h
ΔT	Mean temperature difference between the heat transfer fluid and the metal hydride, °C
ΔH	Metal hydride enthalpy, heat of reaction, kJ/mol_{H2}
ΔS	Metal hydride entropy of reaction, kJ/mol_{H2}-K
η_{PP}	Power plant efficiency
ρ	Metal hydride material bulk density, kg/m^3
ψ	Exergetic efficiency

Subscripts

ic	Property referred to station ic (inlet during charging) as shown in Fig. 3
id	Property referred to station id (inlet during discharging) as shown in Fig 3
oc	Property referred to station oc (outlet during charging) as shown in Fig. 3
od	Property referred to station od (outlet during discharging) as shown in Fig. 3
c	Referred to the charging process
cond	Heat transfer coefficient referred to conductive heat transfer process
conv	Heat transfer coefficient referred to convective heat transfer process
d	Referred to the discharging process
HTMH	High temperature metal hydride
LTMH	Low temperature metal hydride
S	Shell side
T	Tube side

applications [7]. The concept was demonstrated to perform adequately for long operating times [7], but the high cost of the Li material made the system unfeasible for low-cost, solar driven power plants. More recently, attention has shifted to Mg based hydrides for high temperature solar driven systems. This is mainly due to the lower cost of magnesium relative to lithium. Several studies were carried out on Mg-based MH materials, examining the behavior of such systems to store heat at temperatures ranging from 400 to 500 °C. The materials showed gravimetric energy densities in the range of 2160–2520 kJ/kgMg [8], which are about 10 times higher than those of current molten salt systems [6]. Additional studies were also carried out comparing Mg–Fe, Mg–Ni and Mg–Co compounds, identifying Mg–Fe as the most promising compound in terms of economic performance and operating conditions [9]. Other studies have been carried out on systems based on Na–Mg compounds for high temperature heat storage applications (on the order of 500–600 °C). These compounds demonstrated good performance under different operating conditions [10]. Recent studies have been performed to demonstrate the feasibility of a newly developed Na–Mg based material (namely $NaMgH_2F$) as a high temperature and high performance hydride for TES applications [11,12]. When compared to $NaMgH_3$ hydride, $NaMgH_2F$ material showed higher stability and higher operating temperatures (on the order of 550–650 °C). In addition, the $NaMgH_2F$ material system demonstrated the capability to reach lower system cost (approximately 30 $/kWhth) and higher exergetic efficiency (about 86%) [11,12]. The material still needs additional research and development in order to improve its cycling ability at the temperatures of interest [12]. In order to

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