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Performance investigation of thermal energy storage systems using metal hydrides adopting multi-step operation concept

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ABSTRACT

The metal hydride based thermal energy storage (MHTES) technology is an attractive option for concentrating solar power. In this paper, a mathematical model was developed for MHTES systems. The charging and discharging processes of thermal energy were numerically analyzed. As shown in the simulation results, the temporal profiles of the average reacted fraction, the fluid outlet temperature and the hydrogen pressure appear to be repeated in a cyclic manner. The mean value of true temperature boost during the discharging process increases as the flowrate of the heat transfer fluid decreases. When the concept called multi-step charging/discharging operation modes was adopted instead of the conventional one-step reaction operation mode, the outlet temperature fluctuation of the heat transfer fluid of the MHTES system can be weakened. The system performance can be further improved by varying the fluid flow rate and optimizing the operation mode.

Introduction

Thermal energy storage (TES) is an important technology that can contribute to avoiding environmental problems and increasing the efficiency of energy consumption [1]. TES can address the mismatch between the thermal energy demand and supply [2], which is one of the main barriers in implementation of renewable energy, such as solar and wind energy. There are three types of TES technologies, i.e. sensible, latent and thermochemical heat storage. In comparison to sensible or latent heat storage, thermochemical TES technology is an attractive option because it offers higher energy densities. Many reactive materials have been proposed for thermochemical TES, e.g. inorganic hydroxide, metal hydride, ammonia, carbonates and metal oxides [3,4]. Among thermochemical TES technologies, the metal hydride based thermal energy storage (MHTES) has been extensively studied due to its high energy densities, good cyclic stability, self-regulating feature and low corrosiveness [5,6].

Bogdanović et al. [7] built a laboratory-scale high temperature heat storage unit using magnesium hydride and the commercially available alloy Code 5800. They found that the combination of metal hydrides could be used for high temperature heat storage, refrigeration and heat transforming. The idea of a small-scale solar thermal power station including a magnesium hydride TES system was proposed and demonstrated by the Max Planck Institute, the IKE Institute of the Stuttgart University and the HTC Solar Company [8]. Bogdanović et al. [9] reported the operating performance of a

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Symbols

ε	Porosity
λ	Thermal conductivity, W m^{-1} K^{-1}
ρ	Density, kg m^{-3}
Ψ	Fraction of transferred hydrogen, %
A_f	Cross-sectional area of the heat exchanger channel, m^2
c_p	Specific heat, J kg^{-1} K^{-1}
d_i	Inner diameter of the hydrogen storage tank, mm
E	Activation energy, J mol^{-1}
k	Reaction rate constant, s^{-1}
M	Molecular weight, g mol^{-1}
L	Length, mm
n_g	Amount of the hydrogen, mol
$\vec{n}$	Normal vector
p	Pressure, MPa
Q_f	Flowrate of heat transfer fluid, m^3 s^{-1}
r	r-Coordinate, mm
R	Universal gas constant, J K^{-1} mol^{-1}
t	Time, s
T	Temperature, K
U	Heat transfer coefficient, W m^{-2} K^{-1}
V_c	Volume of the container, m^3
wt	Gravimetric hydrogen storage capacity, %
W_s	Weight of metal hydride, kg
X	Reacted fraction
$\overline{X}$	Average reacted fraction
z	z-coordinate, mm
Z	Compressibility factor
ΔH	Reaction heat, J mol^{-1}
ΔS	Reaction entropy, J mol^{-1} K^{-1}
ΔT_{tr}	True temperature boost, K
$\Delta \overline{T}_{tr}$	Mean value of ΔT_{tr}, K

Subscript

a	Absorption
c	Container
d	Desorption
e	Effective value
eq	Equilibrium
f	Heat transfer fluid
g	Hydrogen
i	Inlet
o	Outlet
ref	Reference
s	Magnesium hydride
t	Hydrogen storage tank

steam generator with an integrated MgH_2/Mg heat storage unit, and the heating output was 9.08 kWh at 370 °C and the energy efficient reached 0.796 for the heat storage process without cold production. Sheppard et al. [10] reported the ΔH and ΔS of decomposition of $NaMgH_3$ to NaH and Mg, and they presented that $NaMgH_3$ was a potential solar heat storage material because of its high enthalpy, decomposition to flat plateau, and negligible hysteresis in case that the decomposition Na metal was avoided. Sekhar et al. [11] experimentally studied the effects of hydrogen supply pressure and absorption temperature on the amount of heat stored and thermal energy storage coefficient. Shen and Zhao [12] established a two dimensional mathematical model for the heat releasing process of the Mg/MgH_2 system. They found that the effective heat transfer is the key factor influencing the output power, and the effective thermal conductivity was improved and the reaction time was shortening by the addition of metal foams. Sheppard et al. [13] assessed the installed cost of four metal hydride pairs for high temperature heat storage based on a simplified techno-economic model. They found that the $NaMgH_2F$–$Ti_{1.2}Mn_{1.8}H_{3.0}$ pair had the least cost advantage among four metal hydride pairs due its high enthalpy and operating temperature. Paskevicius et al. [14] constructed a prototype solar thermal energy storage system based on MgH_2 for screening materials under dynamic conditions with active heat extraction. Fang et al. [15] fabricated and tested a laboratory prototype of a thermal battery based on MgH_2–TiMnV hydride pairs. Patrick et al. [16] presented a techno-economic analysis of the new MHTES system. They found that the new $NaMgH_2F$–Na_3AlH_6 pars can achieve a decrease of system installed cost by about 11% and an increase of the system exegetic efficiency of about 5% in compared with the $NaMgH_3$–$NaAlH_4$ pair.

Although some studies were carried out both experimentally and theoretically, little work has devoted to the numerical study of the MHTES system. In this paper, a rigorous mathematical model was established for a MHTES system consisting of a metal hydride reactor and a hydrogen storage tank. Through numerical simulation, the working characteristics of the system in repeated cycles were explored and the performance of the system was assessed. Finally, a novel multi-step operation concept was proposed. The performance of the novel system adopting the multi-step operation concept was assessed and the comparison between the novel system and the conventional one is presented.

Metal hydride based thermal energy storage system

Fig. 1 shows the schematic of the MHTES system. The system consists of a metal hydride reactor, a shut-off valve and a hydrogen storage tank. For the system, there are two operating processes, i.e., the charging process and the discharging

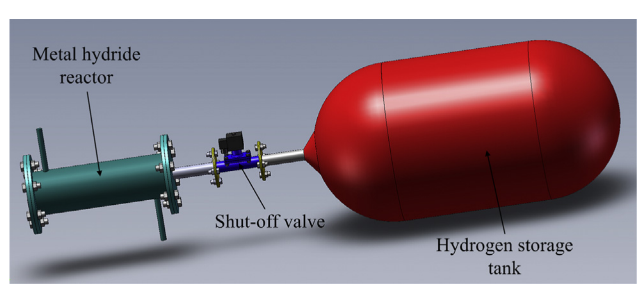

Fig. 1 – The schematic of a metal hydride thermal energy system.