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Performance investigation and optimization of metal hydride reactors for high temperature thermochemical heat storage

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ABSTRACT

The metal hydride based thermal energy storage (MHTES) technology is expected to be an attractive option. Being a key component, the metal hydride reactor should facilitate good heat and mass transfer. In this study, the effects of two heat transfer enhancement measures, i.e. using metal fins and making metal hydride powder into compacts, on the MHTES system performance were evaluated. The heat and mass transfer characteristics in five different reactors using different enhancement measures were compared. As shown in the simulation results, the temperature distributions of the reactors are more uniform when the bed thermal conductivity of the reactors is increased by making metal hydride powder into compacts. Moreover, the average reaction rate is remarkably increased when the measures for heat transfer enhancement are adopted. When the gravimetric heat storage rate (GHSR) is used as a comprehensive evaluation index, the optimum reactor of the MHTES system is not equipped with using any fins but using metal hydride compact technique. Therefore, metal hydride compact technique is recommended in the MHTES applications while expensive metal fins can be removed.

Introduction

Nowadays, concentrating solar power (CSP) is becoming a promising way to use renewable energy. The International Energy Agency's roadmaps set a target of approximately 11% of global electricity production from CSP plants by 2050 [1]. Compared with other renewable energies, CSP can deliver dispatchable power on demand by integrating thermal energy storage (TES) [2]. There are three types of TES technologies for CSP plants, i.e. sensible, latent and thermochemical heat storage. Of the TES technologies, the thermochemical TES technology using metal hydride (MH) is expected to be an attractive option, due to its high energy density and low cost [3]. The heat release rate and the operating temperature of the metal hydride based thermal energy storage (MHTES) can be easily controlled by varying the hydrogen supply pressure [4].

Bogdanović et al. [5] reported the operating performance of a process steam generator with an integrated MgH_2/Mg heat storage unit. They found that the heating output of the heat storage unit was 9.08 kWh at 370 °C and the energy efficiency reached 0.796. Reiser et al. [6] studied the energy density, thermodynamic properties, operating temperature range, cyclic stability and preparation of Mg/MgH_2, Mg–Ni/Mg_2NiH_4,

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Nomenclature

Symbols

ε	Porosity
λ	Thermal conductivity, W m^{-1} K^{-1}
μ	Dynamic viscosity, Pa s
ρ	Density, kg m^{-3}
c_p	Specific heat, J kg^{-1} K^{-1}
E	Activation energy, J mol^{-1}
h_{ex}	Heat transfer coefficient between the MH and either the tube or the fins, W m^{-2} K^{-1}
k	Reaction rate constant, s^{-1}
K	Permeability, m^2
M	Molecular weight, g mol^{-1}
$\vec{n}$	Normal vector
p	Pressure, MPa
R	Universal gas constant, J K^{-1} mol^{-1}
t	Time, s
T	Temperature, K
u, v	Velocity, m s^{-1}
$\vec{u}_g$, $\vec{V}$	Velocity vector, m s^{-1}
wt	maximum mass content of hydrogen in the metal, %
W	Weight, g
X	Reacted fraction
Nu	Nusselt number
ΔH	Reaction heat, J mol^{-1}
ΔS	Reaction entropy, J mol^{-1} K^{-1}
Re	Reynolds number
Pr	Prandtl number

Subscript

0	Initial
a	Absorption
am	Ambient
comp	compacts
d	Desorption
e	Effective value
eq	Equilibrium
f	Heat transfer fluid
fin	Fins
g	Hydrogen
in	Inlet
r	Reactor
s	Magnesium hydride
w	Heat exchanger tube wall
ref	Reference

Mg–Fe/Mg_2FeH_6 and Mg–Co–H systems. Bogdanović et al. [7] found Mg_2FeH_6 was highly suitable material for thermochemical thermal energy storage at around 500 °C due to its high gravimetric/volumetric thermal energy density and excellent cycling stability at the temperature level. Meng et al. [8] found the heat transfer performance of metal hydride reactors played a determinant role in the overall performance of the MHTES system. Sheppard et al. [9] reported that $NaMgH_3$ was a potential solar heat storage material because of its high enthalpy, flat plateau, and negligible hysteresis in case that the decomposition to Na metal was avoided. Sekhar et al. [4] experimentally studied the effects of hydrogen supply pressure and absorption temperature on the amount of heat stored and thermal energy storage coefficient of the Mg-30% $MmNi_5$ based heat storage device. They found the maximum amount of heat stored was 0.714 MJ kg^{-1} and the corresponding thermal energy storage coefficient was 0.74 at a supply pressure of 2 MPa and an absorption temperature of 150 °C. Shen and Zhao [10] established a two dimensional mathematical model for the heat releasing process of the Mg/MgH_2 system. Sheppard et al. [11] presented a simplified techno-economic model to explore the factors that have the largest impact on the costs of using metal hydrides for concentrating solar thermal storage and measured the hydrogen desorption properties of $NaMgH_2F$ for the first time. Even though some studies on the MHTES were conducted in the literature [4–11], metal hydride reactors for high temperature TES have not been fully studied. Generally, metal hydride reactors, in which the metal hydride formation and decomposition occur, play an important role in the MHTES system. However, the poor heat transfer limits the absorption/desorption processes in the metal hydride reactor, which would limit the performance of the MHTES system [12,13]. Thus, different measures to enhance heat transfer have been undertaken: insertion of metal matrices of high thermal conductivity (such as aluminum foam [14], copper wire net structure [15] and multilayer-waved sheet structure [16]), compaction of metal hydride powder with expanded nature graphite (ENG) [17–19] and integration of heat exchanger inside the bed (such as bundle of tubes [20], finned tube heat exchanger [21], spiral heat exchanger [22]). Inserting metal matrices into the hydride bed is commonly used for low-temperature metal hydride reactors. However, solid state diffusion processes can occur between magnesium and metal matrices, which will reduce the hydrogen storage capacity at high temperature (>300 °C) [18]. Therefore, this measure is not recommended to be used for high-temperature metal hydride reactors.

The compaction of metal hydride powder and the integration of finned tube heat exchanger inside the bed are two important measures to enhance heat transfer of the metal hydride reactors for the MHTES. The aim of this study is to evaluate the effects of the two measures on the performance of the MHTES and determine the heat transfer enhancement measures suitable for the metal hydride reactors for the MHTES. In the present study, the gravimetric heat storage rate (*GHSR*) was defined as a comprehensive evaluation index to evaluate the reactor performance for the MHTES system. In addition, a mathematical model was established for the metal hydride reactors for the MHTES system. The model was solved using a finite element package, COMSOL Multiphysics 3.5a (COMSOL, Sweden), and validated with the published experimental data. The heat and mass transfer characteristics in the metal hydride reactors of different configurations were reported and compared.

Performance assessment

The thermal capacity and the charging/discharging time are two key issues in the design of a thermal energy storage