Simulation of high temperature thermal energy storage system based on coupled metal hydrides for solar driven steam power plants

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A R T I C L E   I N F O

Article history:
Received 10 June 2017
Received in revised form 31 August 2017
Accepted 14 November 2017
Available online xxx

Keywords:
Solar power plants
Transport models
Metal hydrides
Thermal energy storage
Hydrogen storage
High temperature

A B S T R A C T

Concentrating solar power plants can achieve low cost and efficient renewable electricity production if equipped with adequate thermal energy storage systems. Metal hydride based thermal energy storage systems are appealing candidates due to their demonstrated potential for very high volumetric energy densities, high exergetic efficiencies, and low costs. The feasibility and performance of a thermal energy storage system based on NaMgH2F hydride paired with TiCr1.6Mn0.2 is examined, discussing its integration with a solar-driven ultra-supercritical steam power plant. The simulated storage system is based on a laboratory-scale experimental apparatus. It is analyzed using a detailed transport model accounting for the thermochemical hydrogen absorption and desorption reactions, including kinetics expressions adequate for the current metal hydride system. The results show that the proposed metal hydride pair can suitably be integrated with a high temperature steam power plant. The thermal energy storage system achieves output energy densities of 226 kWh/m³, 9 times the DOE SunShot target, with moderate temperature and pressure swings. In addition, simulations indicate that there is significant scope for performance improvement via heat-transfer enhancement strategies.

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Introduction

One of the best solutions to produce renewable electric power is represented by concentrating solar power (CSP) plants [1], due to their potential to provide highly dispatchable power [2–5]. However, to achieve low electricity production costs, CSP plants must be coupled with suitable thermal energy storage (TES) systems [6]. With an adequate storage system, the plant can produce electricity continuously at a power level dictated mainly by the plant capacity factor. Currently thermal energy can be stored as sensible heat, latent heat, or thermochemical heat [2,3].

Thermochemical systems utilizing coupled metal hydrides (MHs) are a very appealing option due to the high efficiency, high energy density and potential low costs [7–10]. Recent analyses have demonstrated that MH-based TES systems can achieve volumetric energy densities almost 10 times larger than traditional molten salt systems [7]. They also have the potential for high exergetic efficiencies, on the order of 95%, and lower costs than molten salt systems, approaching the DOE target of 15 $/kWhth [7,8,11]. A MH-based TES system
requires a high-temperature metal hydride (HTMH) to be paired with a low-temperature metal hydride (LTMH). Among the HTMH materials available for TES applications, those based on Na and Mg show several positive characteristics. The Na and Mg class of materials operates at temperatures on the order of 500–650 °C, depending on the MH formulation [7,11,12]. This range of temperatures makes the TES system suitable for integration with solar driven high pressure or supercritical steam power plants, which usually operate at temperatures on the order of 600 °C [13,14]. The Na-Mg metal hydrides have also demonstrated the capability to reach high energy densities [7], high exergetic efficiencies [7,11] and relatively low investment costs [7]. The materials best suited for TES applications and currently available are NaMgH3 and NaH. A third Na-Mg MH formulation, the NaMgH2F material, is being actively examined for thermal energy storage applications [11,12]. The NaMgH2F HTMH material, coupled with a high pressure Ti based LTMH (TiCr1.6Mn0.2), has demonstrated the high potential of NaMgH2F for thermal energy storage use. The material has shown the potential to reach TES system cost lower than 30 $/kWhth when the HTMH is coupled with sodium alanate based LTMH [11,12]. The reduced system cost can be attributed mainly to the low raw material cost and the high reaction enthalpy of 96.8 kJ/molH2 [11,12]. The TES system based on NaMgH2F can also reach exergetic efficiencies on the order of 86% [11] and TES system volumetric energy densities on the order of 240 kWhth/m3, i.e. about 10 times larger than the DOE target of 25 kWhth/m3 [7,12]. However the initial formulation of this material showed some drawbacks relative to the cycling performance, with a remarkable cycling degradation after only a few cycles [11]. This issue has recently been solved with some minor material modifications as discussed and demonstrated in Ref. [16].

The present work focuses on the technical assessment and performance analysis of a TES system comprising the NaMgH2F HTMH material, coupled with a high pressure Ti based LTMH (TiCr1.6Mn0.2). This coupled TES system can achieve operating temperatures of about 600–650 °C, requiring low temperature heat at about 15–30 °C. This makes the proposed TES system suitable for integration with a CSP plant based on an ultra-supercritical (USC) steam cycle operating at approximately 600 °C.

The objective of this work is also aimed to identify the setup and operating conditions for an optimized system configuration. To accomplish this, a laboratory-scale apparatus is simulated using a detailed transport model accounting for mass, energy and momentum balances, as well as

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**Nomenclature and abbreviations**

<table>
<thead>
<tr>
<th>Abbreviations</th>
<th>Symbols</th>
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<tbody>
<tr>
<td>CSP</td>
<td>Concentrating solar power</td>
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<tr>
<td>DOE</td>
<td>US Department of Energy</td>
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<td>GWE</td>
<td>Greenway Energy</td>
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<td>HTMH</td>
<td>High-temperature metal hydride</td>
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<td>LTMH</td>
<td>Low-temperature metal hydride</td>
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<td>MH</td>
<td>Metal hydride</td>
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<td>SRNL</td>
<td>Savannah River National Laboratory</td>
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<td>TES</td>
<td>Thermal energy storage</td>
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<td>USC</td>
<td>Ultra super critical</td>
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<tr>
<td>TIT</td>
<td>Turbine inlet temperature</td>
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</tbody>
</table>

**Variables**

- \( C_a \) Preexponential absorption kinetics factor (s\(^{-1}\))
- \( C_d \) Preexponential desorption kinetics factor (s\(^{-1}\))
- \( C_p \) Specific heat capacity at constant pressure (J/kg K)
- \( E_a \) Absorption activation energy (J/mol)
- \( E_d \) Desorption activation energy (J/mol)
- \( \Delta H \) Enthalpy of reaction for H\(_2\) desorption (J/mol)
- \( h \) Molar enthalpy of H\(_2\) (J/mol)
- \( k \) Thermal conductivity (W/m K)
- \( L \) Fill length of MH in test vessel cavity (m)
- \( M_{H_2} \) Molecular weight of H\(_2\) (kg/g-mol)
- \( n_{SM} \) Molar H\(_2\) storage capacity of MH bed (mol)
- \( P \) Gas pressure (Pa)
- \( P_{atm} \) Atmospheric pressure (Pa)
- \( P_{eq} \) Equilibrium pressure between the MH and the gas (Pa)
- \( q \) Volumetric thermal power input (W/m\(^3\))
- \( Q \) Thermal energy input (J)
- \( Q \) Thermal power input (W)

**Subscripts**

- \( R \) Universal gas constant (J/mol K)
- \( R_v \) Radius of MH cavity in test vessel (m)
- \( S \) Mass rate of production of H\(_2\) gas (kg/m\(^3\)s)
- \( \Delta S \) Entropy of reaction (J/mol K)
- \( T \) Temperature (K)
- \( t \) Time (s)
- \( \overline{u} \) Gas velocity vector (m/s)
- \( \overline{u}_s \) Superficial gas velocity vector (m/s)
- \( X \) Molar concentration of H\(_2\) absorbed within the MH (mol/m\(^3\))
- \( X_m \) Minimum molar concentration of H\(_2\) in MH (mol/m\(^3\))
- \( X_M \) Maximum molar concentration of H\(_2\) in MH (mol/m\(^3\))
- \( \epsilon \) Porosity of the MH bed
- \( \eta \) Efficiency
- \( \eta_d \) Dilatational viscosity of H\(_2\) gas (Pa s)
- \( \mu \) Dynamic viscosity of H\(_2\) gas (Pa s)
- \( \rho \) Mass density (kg/m\(^3\))
- \( \tau \) Viscous stress tensor (Pa)

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Please cite this article in press as: d’Entremont A, et al., Simulation of high temperature thermal energy storage system based on coupled metal hydrides for solar driven steam power plants, International Journal of Hydrogen Energy (2017), https://doi.org/10.1016/j.ijhydene.2017.11.100
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