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

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ABSTRACT

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 TiCr_{1.6}Mn_{0.2} 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

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Nomenclature and abbreviations			
Abbreviations			
CSP	Concentrating solar power	R	Universal gas constant (J/mol K)
DOE	US Department of Energy	R_v	Radius of MH cavity in test vessel (m)
GWE	Greenway Energy	S	Mass rate of production of H ₂ gas (kg/m ³ s)
HTMH	High-temperature metal hydride	ΔS	Entropy of reaction (J/mol K)
LTMH	Low-temperature metal hydride	T	Temperature (K)
MH	Metal hydride	t	Time (s)
SRNL	Savannah River National Laboratory	\vec{v}	Gas velocity vector (m/s)
TES	Thermal energy storage	\vec{v}_s	Superficial gas velocity vector (m/s)
USC	Ultra super critical	X	Molar concentration of H ₂ absorbed within the MH (mol/m ³)
TIT	Turbine inlet temperature	X_m	Minimum molar concentration of H ₂ in MH (mol/m ³)
Variables		X_M	Maximum molar concentration of H ₂ in MH (mol/m ³)
C_a	Preexponential absorption kinetics factor (s ⁻¹)	ϵ	Porosity of the MH bed
C_d	Preexponential desorption kinetics factor (s ⁻¹)	η	Efficiency
C_p	Specific heat capacity at constant pressure (J/kg K)	η_d	Dilatational viscosity of H ₂ gas (Pa s)
E_a	Absorption activation energy (J/mol)	μ	Dynamic viscosity of H ₂ gas (Pa s)
E_d	Desorption activation energy (J/mol)	ρ	Mass density (kg/m ³)
ΔH	Enthalpy of reaction for H ₂ desorption (J/mol)	$\underline{\tau}$	Viscous stress tensor (Pa)
h	Molar enthalpy of H ₂ (J/mol)	Subscripts	
k	Thermal conductivity (W/m K)	H ₂	Associated with H ₂ gas
L	Fill length of MH in test vessel cavity (m)	HTMH	Associated with high-temperature metal hydride
M_{H_2}	Molecular weight of H ₂ (kg/g-mol)	LTMH	Associated with low-temperature metal hydride
n_M	Molar H ₂ storage capacity of MH bed (mol)	MH	Associated with metal hydride (same value for both HTMH and LTMH)
P	Gas pressure (Pa)	MHBulk	Associated with bulk (non-porous) MH material (same value for both HTMH and LTMH)
P_{atm}	Atmospheric pressure (Pa)	PP	Associated with power plant
P_{eq}	Equilibrium pressure between the MH and the gas (Pa)	SS	Associated with stainless steel
\dot{q}	Volumetric thermal power input (W/m ³)	0	Initial condition
Q	Thermal energy input (J)		
\dot{Q}	Thermal power input (W)		

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. This material was extensively studied and characterized by Bouamrane et al. in the late 1990's [15]. Recent investigations have 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 (TiCr_{1.6}Mn_{0.2}). 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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