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Absorption and desorption of hydrogen in long metal hydride tank equipped with phase change material jacket

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ABSTRACT

A numerical study was carried out to address the practical aspects of hydrogen absorption and desorption process in a long tubular $LaNi_5$ metal hydride tank (MHT) integrated with Rubitherm phase change material (PCM) jacket for hydrogen supplying of PEM fuel cell. Different H_2 supply pressures ($p = 10$, 15 and 20 bar), different discharge pressures ($p = 1.5$, 1.75 and 2 bar) and metal hydride bed porosities (0.4, 0.5 and 0.6) were rigorously analyzed to report their influences on transient and local temperature distributions across H_2-MHT system and PCM jacket. The time-dependent changes of hydrogen to metal (H/M) ratio and PCM melt fraction were also investigated until they reach equilibrium. It was found that system temperature, PCM melt fraction and H/M ratio reach steady state with different rates, such that systems with higher supply pressure in absorption, lower discharge pressure in desorption and higher bed porosity approach steady state faster. Up to the steady state, 64%, 79% and 91% of the initial volume of solid PCM liquefies in absorption and 67%, 83% and 95% of liquid PCM solidifies in desorption for bed porosities of 0.6, 0.5 and 0.4, respectively. The MHT is charged with hydrogen much faster under high supply pressures. Also, it is discharged much faster under lower discharge pressure. Inserting metal foam in the PCM jacket enhances the thermal conductivity, and significantly reduces the charging and discharging time.

Introduction

Growing environmental crises such as ozone layer depletion, emission of greenhouse gasses (carbon dioxide, methane, nitrous oxide, and fluorinated gases), and the air pollution by fossil fuels, have attracted vast attentions to substitute the gasoline by renewable and green energy solutions such as hydrogen (H_2). Hydrogen-driven fuel cells, namely alkaline fuel cell and proton exchange membrane fuel cell, are not yet commercially viable due to existing problems in storing the hydrogen. The solid-state metal hydride material has advantages in comparison with the conventional compressed

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Nomenclature

C	heat capacity, J/kg K
C'	mushy zone constant, kg/m^{3}s
C_a	absorption rate coefficient, s^{-1}
C_d	desorption rate coefficient, s^{-1}
C_p	heat capacity at constant pressure, J/kg K
E_a	activation energy for absorption, J/mole
E_d	activation energy for desorption, J/mole
H/M	hydrogen to metal atomic ratio
K	permeability, m^2
K	thermal conductivity, W/m K
l	length of reactor, m
$\dot{m}$	hydrogen mass reaction rate, Kg/m^{3}s
P	absolute pressure, Pa
R_1	radius of inlet, m
R_2	radius of metal hydride tank, m
R_3	radius of PCM Jacket, m
R	universal gas constant, J/mole K
t	time, s
T	temperature, K
U	velocity, m/s
S	source term
H	total enthalpy, J/kg
h	sensible enthalpy, J/kg

Greek letters

ρ	density, kg/m^3
μ	dynamic viscosity, kg m^{-1}s
β	melt fraction
ΔH	enthalpy of absorption, J/mole
ΔH_p	latent heat content, J/kg

Subscripts

0	initial
a	absorption
d	desorption
eq	equilibrium
eff	effective
g	gas
in	inlet
l	liquid PCM
p	PCM in both phases
P	constant pressure
r	r-coordinate
ref	reference
s	solid bed
sat	saturate
sp	solid PCM
z	z-coordinate

gaseous or liquid H_2 cylinders in vehicular applications. High gravimetric and volumetric density, high H_2 absorption capacity, moderate working temperature and moderate charging pressure for H_2 storage, all make the metal hydride tanks (MHT) a considerable choice. Compact size and energy efficiency of metal hydride fuel cells are capable to make them superior choices to batteries in portable applications.

During the last two decades, there have been studies on key parameters such as metal hydride bed kinetic reaction, heat and mass transfer rates of hydrogen that all play significant roles in performance of hydrogen charging process. Several numerical and experimental studies have been performed to develop two-dimensional models of MHTs, and determine the reaction kinetics and equilibrium pressure for $LaNi_5$ hydrogen storage system [1–3]. Muthukumar et al. [4] carried out a numerical investigation on hydrogen absorption performance of $MmNi_{4.6}Al_{0.4}$ storage tanks. They studied the effects of different supply pressures, overall heat transfer coefficients and wall temperatures on the reaction rate between H_2 and metal alloy. Results indicated that increasing the overall heat coefficient up to 1250 w/m^{2}K does not accelerate the absorption time because of high thermal resistance of metal hydride bed. Muthukumar and Ramana [5] studied the effects of different wall boundary conditions and bed thicknesses on H_2 desorption process. They indicated that discharging time mainly depends on the successful heat removal from the bed.

Absorption of hydrogen into metal alloys expands and rearranges its crystalline structure and forms the metal hydride medium. The formation of new bonds generates extra heat that must be removed to an external source. In turn the hydrogen desorption or discharge process requires breaking of bonds, compression of the crystal and hence the heat is sunk from environment. Therefore heat transfer during charge/discharge processes, as the challenging obstacle in utilizing the metal hydride tanks as hydrogen storage, has focused the attentions on integration of MHTs with various heat exchangers. A spiral heat exchanger was designed for a metal hydride tank by Mellouli et al. [6]. Their experimental results showed that the charge/discharge times of the reactor are considerably reduced when a heat exchanger is used. Dhaou et al. [7] utilized a finned spiral heat exchanger to improve the heat transfer and reduce the hydrogen charging time significantly compared to typical spiral heat exchangers. Muthukumar et al. [8] numerically studied the absorption process inside the $MmNi_{4.6}Al_{0.4}$ metal hydride tank equipped with internal cooling tubes and external cooling jacket. Based on the developed 2D mathematical model in cylindrical coordinates, they considered different numbers and various arrangements of cooling tubes to obtain the optimum geometry associated with the minimum absorption time. Askri et al. [9] employed a numerical model to study the hydrogen charge process behavior in different geometries of metal hydride and heat exchangers. They showed that a concentric heat exchanger tube equipped with fins yields efficient absorption rate for hydrogen. McDonald and Rowe [10] also studied the improvements on the external heat transfer from MHTs by attaching additional fins.

Many numerical simulations are implemented to model and economize the heat transfer from metal hydride storages, and hence to reduce the hydrogen absorption time. Freni et al. [11] carried out a computational study on cooling of $LaNi_5$