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Design and investigation of hydriding alloy based hydrogen storage reactor integrated with a pin fin tube heat exchanger

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ABSTRACT

The reaction between metal hydride (MH) and hydrogen gas generates substantial amount of heat. It must be removed rapidly to sustain the reaction in the metal hydride hydrogen storage reactor. Previous studies indicate that the performance of the reactor can be improved by inserting an efficient heat exchanger design inside the metal hydride bed. In the present study, a cylindrical shaped metal hydride system containing $LaNi_5$, integrated with a finned tube heat exchanger assembly made of copper pin fins and tubes, is presented. A 3-D numerical model is formulated in COMSOL Multiphysics 4.4 to study the transient behavior of sorption process inside the reactor. Experimental data obtained from the literature is used to approve the legitimacy of the proposed model. Influence of various operating and geometric parameters on the total absorption time of the reactor has been investigated. It is found that hydrogen supply pressure is the most influencing factor to increase the absorption rate of hydrogen. Total absorption time of the reactor is found to be 636 s with maximum storage capacity of 1.4 wt% at the operating conditions of 15 bar H_2 gas supply pressure, heat transfer fluid temperature of 298 K and flow rate of 6.75 l/min.

Introduction

World's energy demand is rapidly increasing due to growing population and high level of living standards. To fulfill this energy requirement, fossil fuels viz. crude oil, coal and natural gas have been used over last few decades. Increasing level of CO_2 as well as air pollutants and faster depletion of fossil fuels have accelerated the demand of an alternative energy source for the future generation. Among the various available energy sources, hydrogen is considered as a hopeful energy source due to its environment friendly nature. But the major challenge associated with hydrogen fuel is its safety and cost efficient production as well as storage. Currently, various technologies are available through which hydrogen can be produced. Some of the technologies are established in industry whereas others are still in research and development stage. Gallucci et al. [1] published an article on hydrogen production using auto-thermal reforming of ethanol in a fluidized bed membrane reactor. Spallina et al. [2] carried out a techno-economic evaluation for two membrane based technologies which was employed for hydrogen generation using natural gas. Viviente et al. [3] developed a new bio-ethanol membrane reformer for the fuel cell applications to intensify

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Nomenclature

A	vant's Hoff constant, K
B	vant's Hoff constant
C	material constant, s^{-1}
c	hydriding alloy concentration, mol m^{-3}
c_p	specific heat, J kg^{-1} K^{-1}
D	diffusion coefficient, m^2 s^{-1}
E	activation energy, J mol^{-1}
f	Molecular weight, (g mol^{-1})
H_a	activation enthalpy, eV
h	heat transfer coefficient, W m^2 K^{-1}
k	thermal conductivity, W m^{-1} K^{-1}
k_b	Boltzmann constant
MH	metal hydride
$\dot{m}$	mass rate of hydrogen, kg m^{-3} s^{-1}
$\vec{n}$	unit normal vector
P	pressure, Pa
Q_f	flow rate of water, l min^{-1}
R	universal gas constant, J mol^{-1} K^{-1}
T	temperature, K
t	time, s
υ	velocity, m/s

Subscripts

a	absorption
alloy	metal hydride alloy
d	desorption
e	effective
eq	equilibrium
f	heat transfer fluid
g	gas
s	supply
sat	saturation
t	transient
0	initial

Greek letters

ΔH	enthalpy of formation, J kg^{-1}
ε	porosity
ρ	density, kg m^{-3}

the generation of hydrogen. High pressure gas compression and liquefaction methods are the conventional techniques of hydrogen storage. Gas compression method has few drawbacks such as danger of explosion, large quantity of energy requirement for compression and low energy density. Liquefaction method is also not a suitable storage method due to its bulky insulation necessity and high storage cost. Hence, researchers' approach has shifted towards the MH form of hydrogen storage. Hydrides can store the hydrogen reversibly at normal temperature and pressure for a long period of time and is considered to be a safe, compact and cost efficient technique for hydrogen storage. During the absorption of hydrogen, chemical reaction takes place which generates large amount of heat. Metal hydrides are not able to remove the generated heat quickly due to their low thermal conductivity and thus increases the total absorption time of the reactor. Previous studies recommend that placing of an efficient heat exchanger inside the metal hydride bed reduces the total absorption time of the reactor thereby achieving faster heat removal rate.

In the last few years, various considerable research works through experiment and mathematical model have been performed to reduce the total absorption time of the hydrogen reactor. Mazzucco et al. [4] presented a review article on different types of tank and bed geometries, heat removal issues, various heat exchanger designs embedded inside the bed and geometry as well as operative strategy oriented optimization. Mohammadshahi et al. [5] reviewed the previous works numerical model governing equations, assumptions, boundary conditions, solution methods and procedure of selecting optimum L/R ratio for reactor design. Joubert et al. [6] analyzed the lattice expansion in the $LaNi_5$ metal hydride powder by using granulometric measurements and scanning electron microscopy. It was revealed that when $LaNi_5$ metal hydride absorbs the hydrogen, volumetric expansion takes place nearly about 22.4%. Askeri et al. [7] found that at $L/R = 2$, reactor takes the longest time to arrive at next equilibrium stage due to least heat transfer rate. It was also observed that at very high or low values of L/R ratio, heat is transferred only in one direction. For in-between values of L/R ratio, 2-D influences are not negligible. Singh et al. [8] simulated the dynamic behavior of sorption process inside the metal hydride hydrogen storage device integrated with a SS tube brazed with radial circular fins on its outer boundary and validated with experimental results. Mohan et al. [9] carried out numerical simulation of solid state hydrogen storage device to find out the impact of system configuration and operating parameters on the absorption rate of hydrogen. Mohan et al. [10] simulated a $LaNi_5$ based air-cooled annular cylindrical hydrogen storage system consisting of external fins. It was seen that use of external fins enhances the absorption rate of hydrogen inside the MH bed. Garrison et al. [11] optimized the transverse and longitudinal fin designs to enhance the hydrogen absorption inside the hydride bed. Mellouli et al. [12] predicted the volumetric changes of $LaNi_5$ based MH bed during absorption and desorption processes of hydrogen and conducted the experiment to validate the model. Wang et al. [13] established a 3-D numerical model to study the effect of helical coil heat exchanger inserted in a cylindrical MH bed system. Visaria et al. [14] explored a systematic approach to design a heat exchanger for $Ti_{1.1}CrMn$ based high-pressure MH storage system. Muthukumar et al. [15] focused on two different AB_5 MH alloys and conducted experiment to find out the effect of operating conditions on absorption capacity of hydrogen reactor. Ma et al. [16] formulated a 3-D model to study the influence of different fin configurations and operating parameters in a finned multi-tubular MH tank. Dhaou et al. [17] experimentally investigated the effect of finned spiral heat exchanger on the absorption time of MH reactor. Muthukumar et al. [18] found out the influence of different operating conditions and container geometries on the hydriding time of hydrogen storage vessel. Oi et al. [19] carried out simulations of a AB_2 based hydride system embedded with a plate-fin type heat exchanger to examine the heat and mass transfer processes. Mellouli et al. [20] employed a two dimensional model to evaluate the performance of a spiral fin tube heat

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