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Improvement in hydrogen desorption performances of magnesium based metal hydride reactor by incorporating helical coil heat exchanger

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ABSTRACT

Mg-based metal hydride has been viewed as one of the most promising materials for hydrogen storage. However, large amount of reaction heat during the hydrogen absorption/desorption cycles negatively affects the heat and mass transfer, thus leading to poor performances. In this work, helical coil heat exchanger (HCHE) is proposed to be inserted into Mg-based metal hydride reactor for improving the heat and mass transfer. The models on pressure-composition-temperature properties and hydrogen desorption kinetics of Mg-based reactor are firstly established for the simulation through experiments. The comparison of hydrogen desorption performances for the reactors incorporating the conventional straight tube, finned tube and new helical coil heat exchangers is conducted based on numerical simulation. The comparison results show that the HCHE has the best effects on improving the heat and mass transfer characteristics of reactor among the three heat exchangers, due to its secondary circulation. Besides, it is suggested that the influence of hydrogen pressure gradient should be considered for the prediction of the performance of Mg-based metal hydride reactor with HCHE.

Introduction

Mg-based MH (metal hydride) is one of the most promising materials among solid state hydrogen storage materials, due to its high capacity, low cost, safety, good reversibility and being environmentally benign [1–3]. During the hydrogen absorption/desorption cycles, large amount of reaction heat is always accompanied, which is easy to make the hydrogen absorption/desorption reaction suspended. For example, the hydrogen desorption process is endothermic and inevitably causes the reduction of MH bed temperature, lowering the equilibrium pressure at the same time. Once the equilibrium pressure is too low to drive the reaction, the hydrogen desorption process will stop. Therefore, proper thermal management is a key issue for Mg-based MH hydrogen storage reactor, since the thermal effect of the reaction between Mg-based MH and H_2 is remarkable [4].

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Nomenclature

Abbreviation

MH	metal hydride
HTF	heat transfer fluid
HCHE	helical coil heat exchanger

Symbols

ε	porosity
λ	thermal conductivity, W m^{-1} K^{-1}
μ	dynamic viscosity, Pa s
ρ	density, kg m^{-3}
C_d	reaction rate constant, s^{-1}
c_p	specific heat, J kg^{-1} K^{-1}
c	hydrogen content, wt.%
d	diameter of heat exchanger tube, m
d_p	diameter of particle size, m
d_c	helical diameter, m
t_{fin}	thickness of fins, m
p_t	pitch of finned tube or helical coil, m
V	volume of helical coil, m^3
S	surface area of heat exchanger, m^2
$\vec{v}$	velocity vector, m s^{-1}
Q_V	volumetric flowrate of HTF, m^3 s^{-1}
E_d	activation energy, J mol^{-1}
h_f	heat transfer coefficient between HTF and MH, W m^{-2} K^{-1}
K	permeability, m^2
L	length, m
l	heat diffusion length, mm
M	molecular weight, g mol^{-1}
m_H	hydrogen mass desorbed per unit volume and time, kg m^{-3} s^{-1}
$\vec{n}$	normal vector
p	pressure, atm
R	universal gas constant, J K^{-1} mol^{-1}
R_{reac}	radius of cylindrical reactor, m
t	time, s
T	temperature, K
i	curvature ratio
X	reaction conversion
N_u	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
e	effective value
eq	equilibrium
f	heat transfer fluid
fin	finned tube
g	hydrogen
inl	inlet of hydrogen
m	MH
Min	minimum value
p	particles of MH
s	straight tube
h	helical coil
ref	reference
reac	reactor

Many approaches have been attempted to improve the heat and mass transfer behaviors of Mg-based MH reactor, such as enhancing the effective thermal conductivity of MH beds [5–8], equipping fins of different materials [9–11] and incorporating heat exchanger into MH reactors [12–16]. Chaise et al. [5] reported that adding ENG (expanded nature graphite) into Mg-based MH could drastically improve the thermal conductivity of MH beds in the radial direction of reactor. It was found that the relationship between the thermal conductivity and ENG content is approximately linear. Bao et al. [7,8] investigated the heat and mass characteristics of Mg-based MH reactor filled with compacted disks made of MgH_2 and 5 wt.% ENG. This kind of compacted disks remarkably improve the thermal conductivity of MH beds, and is recommended for MH based heat storage systems. However, Bao et al. also indicated that the variation of MH beds thermal conductivity makes little difference in the average reaction conversion and fluid outlet temperature. Besides, pressing MH and ENG powder into compacted disk not only lowers the gravimetric hydrogen storage capacity but also reduces the MH beds porosity and hydrogen permeability, thus weakening the mass transfer process. The structure stability of the compacted disks during the hydrogen absorption/desorption cycles is still uncertain. Unlike enhancing the thermal conductivity of MH beds, incorporating fins or heat exchangers into the reactor makes both the heat transfer and mass transfer characteristics improved by increasing heat exchanger area. It has been proven to be an effective way to enhance heat and mass transfer, thus improving hydrogen storage performances of Mg-based MH reactor. Nyamsi et al. [9] derived a semi-analytical expression of heat transfer rate of the annular fin to evaluate the finned tube heat exchanger design. Three different fin materials, including Al, Cu and stainless steel, were compared. Fin made of Al is suggested to use in the MH hydrogen storage reactor due to its high thermal conductivity, low density and cost. Chung et al. [12,13] compared the heat transfer characteristics of MH reactors equipped with concentric heat exchanger tube and heat pipe. The heat transfer for hydrogen absorption/desorption is improved by incorporating either the concentric heat exchanger or heat pipe into the reactors. In addition to the enhancement of heat transfer, the heat pipe also effectively avoids water leaking out of heat exchanger tubes. Garrier et al. [14] tested the hydrogen absorption/desorption behavior of a large-scale MH reactor equipped with heat exchanger, and discovered that the absorption/desorption behavior is strongly dependent on the heat exchanger. For a large-scale reactor, the heat transfer efficiency of internal heat exchanger is much higher than that of external heating system, which is commonly used for the small-scale reactor.

In recent years, incorporating the HCHE (helical coil heat exchanger) into MH reactor has been increasingly investigated

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