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Investigation on the influences of heat transfer enhancement measures in a thermally driven metal hydride heat pump

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ABSTRACT

Metal hydride heat pump (MHHP) can be utilized in a variety of applications and shows great potential in recovery of low-grade heat. Being its kernel component, the reactors should facilitate good heat and mass transfer to achieve satisfactory system performance. In this paper, the influences of certain heat transfer enhancement measures for the reactors were investigated by numerical simulation and thermodynamic analysis. Three types of reactors packed with metal hydride powder, metal hydride powder/Al foam and metal hydride compact were taken for discussion. As shown in the simulation results, for the MHHP adopting heat transfer enhancement, the coefficient of performance tends to reduce slightly while the specific heating power increases remarkably. Therefore, these measures work positively and are recommended for use in heat pump applications.

1. Introduction

In recent years, the exhaustion of fossil fuel, such as oil, coal and natural gas has been the worldwide concern. To alleviate the pressing situation, the efficient use of the various energy resources is desirable. As a promising candidate in fulfilling this purpose, the thermally driven metal hydride heat pump (MHHP) has attracted many attentions. The MHHP system is based on the following reversible reaction

$$M + \frac{x}{2}H_2 \leftrightarrow MH_x + \Delta H \tag{1}$$

where M stands for a certain kind of metal or alloy, MH_x is the reaction product, namely metal hydride (MH). The absorption/desorption of hydrogen is accompanied with significant heat effect, which makes it possible to be applied for heating or cooling. Actually, different thermal cycles can be formed for MHHP to achieve refrigeration, heat amplification or heat upgrading. A wide range of working conditions from −50 to 400 °C is covered by choosing different materials. What is more, the system can be effectively driven by low-grade heat, e.g. the heat from solar energy [1], the industrial waste heat [2] and the heat from vehicle exhaust gas [3,4].

In spite of these advantages, the performance of MHHP is not so satisfactory due to a few factors, e.g. the poor heat transfer in the metal hydride reactor [5]. According to Hahne and Kallweit.[6], the effective thermal conductivity of the MH powder is generally around 1 W/(m K), which suggests sluggish heat transfer and low output power. So far quite a few measures have been presented to solve this problem by increasing thermal conductivity of MH bed, mainly following two routes. The first route is to improve the structural design by inserting heat conduction matrices. The matrices, often made of metals with high thermal conductivity (>100 W/(m K)), can provide a large void fraction of >0.9 for the reactor bed in MHHP. Their geometries vary,

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Nomenclature

A	parameter in P–C–T equation
B	parameter in P–C–T equation, K
C_p	specific heat capacity, J/kg K
E	activation energy, J/mol
h	convective heat transfer coefficient, W/m^2 K
ΔH	reaction heat, J/mol H_2
$[H/M]$	hydrogen to metal ratio
k	reaction rate constant, s^{-1}
K	permeability, m^2
$\dot{m}$	mass source term of reaction, kg/m^3 s
L	length of the tubular reactor, m
M	molecular weight, kg/mol
N	amount, mol
P	pressure, Pa
q	mass flow rate, kg/s
r	r-coordinate, m
R_g	general gas constant, J/mol K
t	time, s
T	temperature, K
U	gas velocity, m/s
W	mass, kg
X	reacted fraction
z	z-coordinate, m

Greek symbols

α	ratio of thermal mass
β	hysteresis factor in P–C–T equation
ε	volume fraction
λ	thermal conductivity, W/m K
μ	dynamic viscosity, Pa s
ρ	density, kg/m^3
ϕ	plateau flatness factor in P–C–T equation
ϕ_0	plateau flatness factor in P–C–T equation
ψ	fraction of transferred hydrogen

Subscripts

a	absorption
b	bulk
c	cycle
d	desorption
e	equilibrium
eff	effective
ex	exerted
f	heat transfer fluid
g	hydrogen gas
H	high
i	inner
in	inlet
L	low
M	intermediate
MH	metal hydride
o	outer
sat	saturated

including circular or longitudinal fins [7], wire matrix, multiple-waved sheet, corrugated helical band [8]. The most popular one ever developed is Al foam [9–11]. The second route is use of metal hydride compacts. This method was first proposed by Ron et al. [12], and further developed by Kim et al. [13–15] and Klein et al. [16,17] through more relevant studies. By means of mixing with binder materials and subsequent pressing process, the powder metal hydride is made into compacts which enable excellent heat transfer. Generally the effective thermal conductivity of the reactor bed can be increased up to 5 W/(m K) or more after adopting the above measures.

However, it is noteworthy that these measures introduce multiple effects rather than merely enhanced heat transfer. For example, the thermal mass of the system is also increased, which would cause additional sensible heat loss and hence affect the thermal efficiency. Therefore the influences of these measures are complicated and need to be quantitatively evaluated. So far only a few relevant studies were reported to address this issue. Isselhorst et al. experimentally tested the effect of several heat conduction matrices using coupling MH reactors [8], and a remarkable increase in the transferred hydrogen flow was found for the reactors with matrices. Kim et al. carried out a series of studies on the MH compacts, including analyses of the performance of a compressor driven MHHP using compacts [15]. A high specific cooling power of 0.8 kW/kg alloy was obtained by the experimental system, indicating that the compacts worked positively. Laurencelle et al. conducted both theoretical and experimental studies on the Al foam matrix [18], large geometry was proved to be viable for the MH reactor with Al foam to attain fast reaction rate, and a 40 ppi Al foam was recommended for application. These findings are useful for the general engineering practice, yet still insufficient for people to clearly understand the role of the various measures in a thermally driven MHHP, especially that concerning the system performance.

In this paper a local thermal equilibrium model describing the coupling process in the MH reactors with or without heat transfer enhancement was formulated, with the temperature variation along the axial direction considered. The dynamic characteristics of the reactors were simulated using the model. The results were analyzed and correlated to the performance of MHHP by a thermodynamic analysis, and thus the effects of the measures for heat transfer enhancement were assessed in detail.

2. Operation principle and system performance

2.1. Operation principle

A single stage MHHP for heat upgrading was considered. It is composed of at least two reactors coupled by the hydrogen pipeline, and two kinds of metal hydrides are packed respectively in the two reactors, as shown in Fig. 1a. A general working cycle was supposed to proceed in 4 steps below, and the corresponding thermodynamic cycle was shown in the Claperon diagram (Fig. 1b).