INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 38 (2013) 7178–7187

Available online at www.sciencedirect.com

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Studies on metal hydride based single-stage heat transformer

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ARTICLE INFO

Article history:
Received 28 September 2012
Received in revised form
15 February 2013
Accepted 11 March 2013
Available online 25 April 2013

Keywords:
Metal hydride
Heat transformer
Performance test
Heat and mass transfer

ABSTRACT

In this manuscript, experimental and numerical studies on a single-stage metal hydride based heat transformer (MHHT) are presented. A prototype of a single-stage MHHT is built and tested for upgrading the waste heat available from 393–413 K to about 428–440 K using $LaNi_5/LaNi_{4.35}Al_{0.65}$ pair. The transient behavior of hydrogen exchange associated with heat transfer is presented for a complete cycle. The effects of heat source temperature and heat rejection temperature on the performance of MHHT in terms of coefficient of performance (COP_{HT}), specific heating power (SHP) and second law efficiency (η_E) are investigated. At the given operating conditions of heat output temperature 428 K, heat input temperature 413 K and heat sink temperature 298 K, the experimentally predicted COP_{HT} and SHP are 0.35 and 44 W/kg, respectively. Both COP_{HT} and SHP are found to increase with the heat source temperature. The numerically predicted results are in good agreement with the experimental data.

1. Introduction

The concept of thermally operated heat pump based on the reversible reactions between the hydrogen gas and a pair of metal hydride alloys was first suggested by Vanmal [1]. The simplest metal hydride based heat pump (MHHP) consists of a high temperature reactor and a low temperature reactor with hydrogen gas as the working fluid. These two reactors are thermally insulated from each other but the hydrogen gas transfers (mass transfer) between them freely. Metal hydride based heat pumps work in three different operating modes: heat upgrading, heat amplification and refrigeration. Metal hydride based heat transformer (MHHT) is a first mode of heat pump which can upgrade the temperature of low grade heat (120–140 °C) such as industrial waste heat, solar energy, geothermal energy, etc. up to the temperature range of 150–220 °C. It also provides higher heat storage capacity and wide range of working temperatures as compared to other conventional heat pumps / heat transformers. In addition, MHHTs use hydrogen as working fluid which is environment friendly and offer noise free and vibration less operation.

Tuscher et al. [2] developed a prototype of MHHT for upgrading the water temperature from 338.5 K to 356 K using $LaNi_{4.7}Al_{0.3}/MmNi_{4.5}Al_{0.5}$. They found that the device was sensitive to the design characteristics of the hydride bed and the container. The first experimental prototype of double-stage MHHT was built by Suda et al. [3] during 1991. The device was designed to a capacity of 7.72 kW employing $LaNi_{4.28}Al_{0.23}/MmNi_{4.57}Al_{0.46}Fe_{0.05}/MmNi_{3.98}Fe_{1.04}$. Subsequently, similar prototypes have been built and tested at IKE, University of Stuttgart, Germany [4–6]. Werner and Groll [4] tested three types of Mm–Ni based alloys at different driving pressures and temperatures to evaluate the thermal behavior of the reaction beds. Using these three alloys, they proposed a double-stage MHHT scheme. In a continuation with the research work reported in [4], Isselhorst and Groll [5] developed a prototype of double-stage MHHT for upgrading heat from 130–140 °C to 200 °C using $LmNi_{4.85}Sn_{0.15}$/

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0360-3199/$ – see front matter
http://dx.doi.org/10.1016/j.ijhydene.2013.03.135

Nomenclature

C_p	specific heat, J/kg K
E	activation energy, J/mol H_2
h	overall heat transfer coefficient, W/m^2 K
K	permeability, m^2
m	mass flux of hydrogen, kg/m^3 s
m_f	mass flow rate of the HTF, kg/s
M_g	molecular weight of hydrogen, kg/kmol
P	pressure, bar
Q	heat transfer, kW
R	reaction rate constant, s^{-1}
R_u	universal gas constant, J/mol K
t	time, s
T	temperature, K
ΔT_{tr}	true temperature lift, K
u	velocity, m/s
X	hydrogen concentration, (H/M ratio)

Greek symbols

β	hysteresis factor
ΔH	enthalpy of reaction, J/mol H_2
ΔS	entropy of reaction, J/mol H_2 K
ε	porosity
ν_g	kinematic viscosity, m^2/s
λ	thermal conductivity, W/m K
φ, φ_o	slope factors
μ_g	dynamic viscosity, kg/m s
ρ	density, kg/m^3

Subscripts

a	absorption
A	low temperature reactor
B	high temperature reactor
d	desorption
e	effective
eq	equilibrium
f	fluid, Final
fi	HTF inlet
fo	HTF outlet
r	reactor
g	gas
m	metal
max	maximum
min	minimum
ss	saturation solid

$LmNi_{4.49}CO_{0.1}Mn_{0.205}Al_{0.205}/LmNi_{4.08}Co_{0.2}Mn_{0.62}Al_{0.1}$. The reported COP and specific power output were about 0.27 and 38 W/kg of alloy, respectively. Later, Willers and Groll [6] built a prototype of double-stage MHHT in star-scheme using six reactors to obtain quasi-continuous power output of about 7 kW. Kang and Yabe [7] developed a thermal model for predicting the performances of a single-stage MHHT employing $LaNi_5/LaNi_{4.5}Al_{0.5}$alloy pair. Gopal and Murthy [8] numerically predicted the performance of a single-stage MHHT employing $ZrCrFe_{1.4}/LaNi_5$ and also investigated the effects of thermal conductivity, bed thickness and overall heat transfer coefficient on the COP of the system. Kumar et al.[9] discussed a method for selecting the suitable alloy pairs for MHHT and MHHP applications by performing a simple thermodynamic analysis. It was found that with a single-stage MHHT, the temperature boost up to 30–70 °C could be possible. Sun et al. [10] discussed a practical method to select the hydride alloys for MHHT. Yang et al. [11] presented a numerical analysis of MHHT employing $LaNi_5$ /$LaNi_{4.7}Al_{0.3}$ and they reported an average temperature boost of 6.8 K with a heat input temperature of 358 K. In another study by Yang et al. [12], the parametric analysis of single-stage MHHT using a mathematical model was presented. Muthukumar and Groll [13] presented a comprehensive review on metal hydride based heating and cooling systems, and also discussed the possible ways for improving the COP and specific cooling/heating capacity.

In view of the above literature survey, it is observed that many authors [7,8,11,12] numerically studied the performance of the single-stage MHHT systems at different operating conditions but their numerical results were not validated with the experimental data. Few investigators presented the thermodynamic analysis [10] and also tested the double-stage MHHT [3–6]. Tuscher and Weinzier1 [2] attempted the experimental investigations of a single-stage MHHT working with $LaNi_{4.7}Al_{0.3}/MmNi_{4.5}Al_{0.5}$ alloy pair. However, their operating temperatures were rather low (<373 K) and also the temperature lift was limited to only 17.0 K from the heat source temperature of 338.5 K. The effects of heat source temperature and heat rejection temperature on performance of the system were not reported.

At IIT Guwahati, the authors research group have successfully developed several thermal models for predicting the performances of the metal hydride hydrogen storage devices [14,15], heat pump [16] and hydrogen compressor [17]. Recently, a thermal model for predicting the performance of the MHHT has been also developed. In order to validate the numerical results, a prototype of MHHT has been built. Hydride alloy pair chosen for the present experimental studies is $LaNi_5$/$LaNi_{4.35}Al_{0.65}$ which is one among the best alloy pair for single-stage MHHT reported in the literature [7,11,12]. The objectives of the present experimental investigation are (i) validation of the numerical results, (ii) finding the maximum possible temperature lift and (iii) investigating the influences of heat input and heat sink temperatures on the performances of the MHHT.

2. Operating principle

Fig. 1 shows the operating principle of a single-stage MHHT on van't Hoff plot. The operating cycle consists of two coupled heat and hydrogen transfer processes (ab and cd) and two sensible heat transfer processes (bc and da). The single-stage MHHT operates in three temperature limits viz., heat output (T_H), heat input (T_M) and heat rejection (T_L). Initially, reactor A is fully hydrided at heat source temperature T_M and reactor B is dehydrided at heat output temperature T_H. During the process ab, reactor A desorbs hydrogen by taking the heat at T_M and