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Experimental research on refrigeration characteristics of a metal hydride heat pump in auto air-conditioning

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Abstract

Refrigerating experiments of metal hydride heat pump were conducted under three operating temperatures. The high pressure reaction bed is filled with $LaNi_{4.61}Mn_{0.26}Al_{0.13}$, while the low pressure reactor is filled with $La_{0.6}Y_{0.4}Ni_{4.8}Mn_{0.2}$. The results show that there are four processes for high-pressure reaction bed, and three processes for low-pressure reaction bed. The lowest refrigerating temperatures at the three operating temperatures are 6.5, 2.5, and 1.9 °C, respectively. Cooling power output cannot be kept constant and becomes smaller as the refrigerating process goes on. As T_h increases, the refrigeration cycle time, temperature and pressure of high reaction beds all climb and COP and cooling power output keep increasing. There is a great deviation between the static van't Hoff plots and the actual dynamic lnP–1000/T relations under the operating temperature of $T_h/T_m/T_l = 150\,°C/30–32\,°C/20\,°C$.

Keywords: Metal hydride; Refrigeration; Heat pump; Coefficient of performance (COP)

1. Introduction

Vapor-driven compression heat pumps usually use CFC refrigerants and have ozone depletion potential and global warming potential. So thermally driven metal hydride heat pumps, which have no mechanical moving parts and saves energy utilizing low-grade heat, compete to be an environmental-friendly alternative. Terry [1] first presented the idea of a metal hydride heat pump and the first experimental research of the prototype was carried out by Gruen [2]. Relative theoretical analysis and experimental research have attracted considerable attention in metal hydride engineering [3–6]. In Ref. [7], the authors of this paper analyzed the refrigeration performance and applicability of metal hydride heat pumps in auto air-conditioning.

Increasing importance is being given to the properties of the hydrogen storage alloys [8], the characteristics of the heat and mass transfer within the reaction bed [9] and the optimum structure design [10] to improve the efficiency and performance of the metal hydride heat pump. In the present work, the experimental set-up of metal hydride heat pump was established and four reaction beds with fins improving heat and mass transfer were adopted to ensure successive heat pumping and heating processes. $LaNi_{4.61}Mn_{0.26}Al_{0.13}$ and $La_{0.6}Y_{0.4}Ni_{4.8}Mn_{0.2}$ were selected as the paired metal hydride. In the experiments, the authors investigated the refrigeration cycle time, the lowest available refrigeration temperature, the values of coefficient of performance (COP) and cooling power output under different operating temperatures. Much difference was found between the static van't Hoff plots and the actual dynamic lnP–1000/T relations.

2. Characteristics of the selected metal hydride pair

Considering the effects of hysteresis, plateau slope and variation in bed pressure [5], two metal hydrides are suitable for the heat pump system in auto air-conditioning. The hydriding alloys selected for this experiment were $LaNi_{4.61}Mn_{0.26}Al_{0.13}$ as the high pressure hydride and $La_{0.6}Y_{0.4}Ni_{4.8}Mn_{0.2}$ as the low pressure hydride. Alloys were activated with 99.99% pure hydrogen. The static hydrogen storage characteristics at several temperatures were tested after several absorption and

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Nomenclature

T_h	high heat resource temperature, °C
T_l	refrigeration temperature, °C
Q_c	cooling power output, kJ
W_R	reaction bed weight, kg
T_m	medium heat resource temperature, °C
ΔH	molar reaction enthalpy, kJ/mol H_2
Q_h	heat supply from heat source, kJ
ΔX	mass of hydrogen in reaction, H/M
M	molar mass of alloy, kg/k mol
C_R	specific heat capacity of reaction bed, kJ/kg °C
λ	efficiency of sensible heat recovery
ΔS	molar reaction entropy, J/K mol H_2
C	specific heat capacity of alloy, kJ/kg °C
n	atom number in metal hydride, atom/alloy
W	alloy weight, kg

Subscripts

1, 2	metal hydride M_1H, M_2H

desorption cycles as shown in Figs. 1 and 2. The reaction enthalpies ΔH and entropies ΔS were calculated using van't Hoff plots and listed in Table 1.

Fig. 3 shows van't Hoff plots of refrigeration cycle at T_l of 10 °C level, where T_h is 150 °C and T_m is 40 °C in auto air-conditioning. It can be seen from the figure that the pressure difference between the two alloys is sufficiently large to shorten the refrigeration cycle time, improve cooling power output and decrease the mass and volume of heat pump system. Furthermore, the pressure of high pressure alloy during hydrogen-desorbing process is not very high, which is advantageous for the operation of refrigeration cycle and manufacture of the reaction beds. The calculation formula for COP in an ideal continuous cycle is as follows [11]. The calculated theoretical COP is 0.5

$$\mathrm{COP} = \frac{(\Delta X_2 n_2 (W_2/M_2)/2)\Delta H_2 - (W_2C_2 + W_{R2}C_{R2})(T_m - T_l)(1-\lambda)}{(\Delta X_1 n_1 (W_1/M_1)/2)\Delta H_1 + (W_1C_1 + W_{R1}C_{R1})(T_h - T_m)(1-\lambda)}. \quad (1)$$

3. Experimental

The experimental apparatus, mainly consisting of four reaction beds, hydrogen line, heat transfer media, is illustrated schematically in Fig. 4. The configuration of the designed bed is different from those in Refs. [12,13]. The cylinder reaction bed is composed of four concentric tubes. The innermost copper tube acts as the heat-transfer liquid passage. The next annular space is equipped with copper fins and filled with a metal hydride alloy. Hydrogen filter is placed outside the alloy. The outermost is a hydrogen jacket. Fins and the hydrogen filter increase the contacting area of alloys and hydrogen and upgrade the heat and mass transfer rate.

Heat-transfer liquid at constant temperature is circulated through the reaction bed in the innermost copper tube. Reaction bed with outermost diameter of 50 mm is about 500 mm in length and contains 2.75 kg of metal hydride alloys. The high pressure reaction bed is filled with $LaNi_{4.61}Mn_{0.26}Al_{0.13}$, while the low temperature reactor is filled with $La_{0.6}Y_{0.4}Ni_{4.8}Mn_{0.2}$. All the reactors are identical in shape and size. The particle size of the alloy powder is less than 3.0 mm. Repeated hydriding and vacuumizing activation process were carried out before the experiments to remove the impurities and water adsorbed in the metal hydrides.

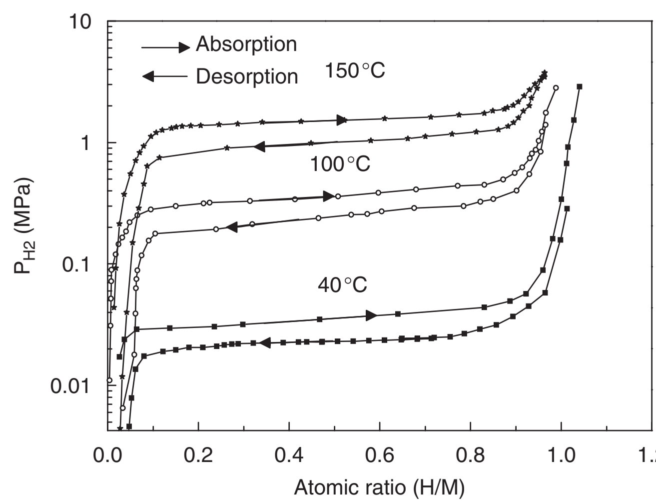

Fig. 1. P-C-T curves of $LaNi_{4.61}Mn_{0.26}Al_{0.13}$.

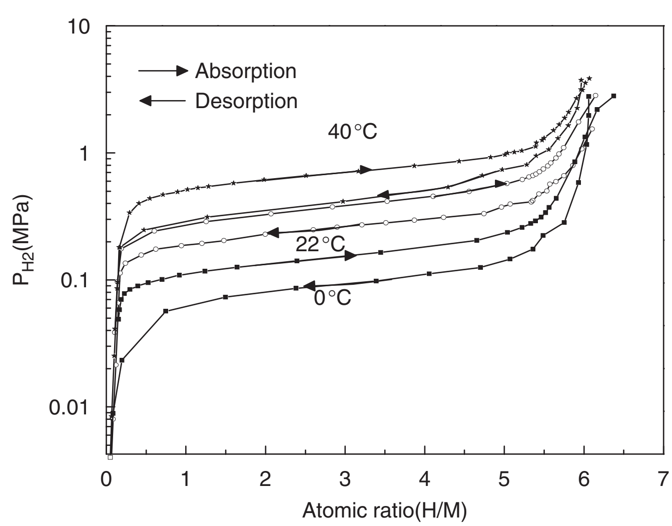

Fig. 2. P-C-T curves of $La_{0.6}Y_{0.4}Ni_{4.8}Mn_{0.2}$.

Pure hydrogen of 99.999% was adopted to react with the alloys. The temperatures of the heat-transfer media were controlled by thermostat baths. Heat-transfer oil (HD-320) was used for the high pressure reaction beds, allowing its operation