

Research on Performance of Metal Hydride Cooling System

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Abstract: Present situation and status of research of metal hydride heat pumps were introduce. The thermodynamics process of hydride cooling system was analyzed. A 2-dimensional model were made respectively. The dynamic mass and heat transfer process in hydride bed was analyzed. The performance parameters, such as cooling power and refrigeration coefficient of performance were calculated and analyzed. The trends along with time of various calculated parameters, such as hydrogen concentration and temperature in reaction bed, pressure and temperature of hydrogen gas, heat exchanged between reaction bed and heat transfer fluid were analyzed. The effects on system coefficient of performance of all kinds of design parameters, such as thickness and conductivity of reaction bed, cycle time, were studied. It can be seen that low conductivity in hydride bed limits the performance of system evidently. Different measures should be taken to enhance the conductivity in bed, such as thinner bed, metal foam, mixing hydride powder with copper or aluminum powder sintered into small balls. Continuous cooling capacity can be produced by two hydride systems. Regenerative heat exchange between pre-heating and pre-cooling process of hydride systems was considered. The results show that the system coefficient of performance was increased by proper duration of regenerative heating.

Keywords: Numerical simulation, Metal hydride cooling system, 2-dimensional model, Heat and mass transfer

NOMENCLATURE

T temperature of metal-hydride beds(K)
 t time(s)
 λ heat conduct coefficient of metal-hydride beds (W/(m·K))
 ρ_b efficient density of metal-hydride beds(m³/kg)
 ρ_{MH} density of hydride(m³/kg)
 ξ ratio of spacing
 β molar number of hydrogen gas adsorbed by hydride per mass in a second
 ΔH activation enthalpy (kJ/kmolHydrogen)
 n_{MH} number of metal atom in hydride molecule
 C concentration of hydrogen gas in metal-hydride beds
 k_{0a} ratio constant
 k_{0d} ratio constant
 E_a activation energy of adsorption process
 E_d activation energy of desorption process
 R hydrogen gas onstant
 T_a temperature of adsorption bed(K)
 T_d temperature of desorption bed(K)
 p pressure of hydrogen gas(Pa)

p_{eqa} equilibrium pressure of adsorption bed(Pa)
 p_{eqd} equilibrium pressure of desorption bed(Pa)
 C_{max} maximum concentration of hydrogen gas
 C_a hydrogen gas concentration of adsorption bed
 C_d hydrogen gas concentration of desorption bed
 mol_{H_2} hydrogen gas molar number
 T_g temperature of hydrogen gas(K)
 V_g specific volume of hydrogen gas(m³/kg)

1. INTRODUCTION

Since the early 1970s, extensive research has been carried out to study mental-hydrogen system.. This has resulted in the development of a wide variety of application: hydrogen storage, hydrogen purification, hydrogen recovery and separation, thermal compressors and energy-conversion systems. Amongst them, energy conversion systems are the most interesting applications. In these systems, it is possible to realize refrigerating, heat pumping and heat transforming with the possibilities of using waste heat and solar energy. There has been a lot of fundamental research work on developing metal hydride technology. These studies include: Many metals and alloys adsorb or desorb hydrogen and form chemical hydrides

depending upon temperature and pressure. The process of adsorption or hydriding is exothermic and the dehydriding process is endothermic. Specially developed porous metal hydrides or misch metal matrix alloys, containing Ni, Fe, La, Al, H, have very high rates of sorption and heats of adsorption when hydrogen is used as the adsorbate. Experimental results are promising in development of metal hydride refrigeration and heat pump systems. Since the early 1980s, the number of investigations around the world have increased considerably. Suda in an experimental investigation of metal hydriding alloys, MmNi_{4.0}Fe_{1.0} and LaNi_{4.65}Al_{0.3}, found that the cooling COP can be increased from 0.2 to 0.45 with increasing heat source temperature from 393 K to 433 K. Nagel et al. developed a metal hydride refrigerator having cooling capacity of 1.7 kW and cooling COP of 0.32, which employed metal hydride powders of MmNi_{4.0}Fe_{1.0} and LaNi_{4.65}Al_{0.3} packed with aluminium foam to increase conductivity. Ron developed a cooling unit suitable for bus air conditioning using a similar pair of metal hydrides. Yanoma et al. developed a large scale metal hydride heat pump which produced heating output of 174 kW and cooling power of 93 kW in an optimum cycle time of 10 min. Charters et al. produced a comprehensive review of investigations on metal hydride heat pumps.

These fundamental studies are essential to the development of metal-hydride heat-pump systems. However, optimum designs and 2-dimensional model of metal-hydride beds have still been seen less. So A 2-dimensional model was made.

2. 2-DIMENSIONAL MODEL OF METAL-HYDRIDE BEDS

Metal-hydride beds adopted were cylinder. Cylinder metal-hydride beds can be described as fig.1.

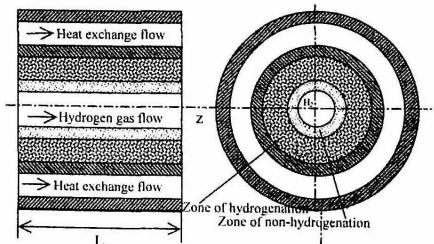


Fig1. Sketch map of 2-dimensional of Cylinder metal-hydride bed

The inner cylinder pipe is filter. Hydrogen gas can flow in the inner cylinder pipe and penetrate the wall of inner cylinder pipe and have the reaction of hydrogenation with metal hydride. The power of metal hydride can not penetrate the filter. Materials filled between filter and its outer metal cylinder is granule of metal hydride. Heat transfer medium can flow in the circularity space between metal-hydride bed outer wall and its closet inner cylinder pipe. 2-dimensional model of metal-hydride beds is based on the following hypotheses:

- 1) Heat convection transfer is ignored between hydrogen gas and granule of metal hydride.
- 2) Drop of pressure when hydrogen gas flows through metal-hydride bed is ignored.
- 3) Heat transfer between metal-hydride bed and heat transfer flow is only considered with considering heat transfer between metal-hydride bed and its ambient space as adiabatic.
- 4) Heat conduct coefficient and specific heat of metal-hydride bed are considered as constant not changing with concentration and pressure of hydrogen gas.
- 5) Hydrogen gas is considered as ideal gas. Thermodynamic parameters of hydrogen gas in metal-hydride bed only change with time but not with space.
- 6) Hydride and hydrogen gas in metal-hydride beds are equilibrium state at the beginning of reaction. Effect of hydrogen gas velocity and heat transfer on parameters of P-C-T equation is not considered, equilibrium pressure of hydrogen gas is still calculated by P-C-T equation of static state.

2-dimensional model of metal-hydride beds can be described as the following equations:

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho_b c_b} \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{\beta \cdot \Delta H}{c_b}$$

$$\beta = \frac{1000 n_{MH}}{2 M_{MH}} \cdot \frac{\partial C}{\partial t}$$

$$\rho_b = \rho_{MH} (1 - \xi)$$

$$\frac{\partial C}{\partial t} = \begin{cases} k_{0a} e^{-E_a/(RT_a)} \ln \left(\frac{P}{P_{eqa}} \right) (C_{max} - C_a) \\ k_{0d} e^{-E_d/(RT_d)} \ln \left(\frac{P_{eqd}}{P} \right) C_d \end{cases}$$

$$p = \frac{mol_{H_2} \cdot R \cdot T_g}{V_g}$$

The initial conditions of the system are:

$$T(r, z, t) = T_0 \quad (t = 0, r_i \leq r \leq r_o, 0 \leq z \leq l)$$

$$C(r, z, t) = C_0 \quad (t = 0, r_i \leq r \leq r_o, 0 \leq z \leq l)$$

The boundary conditions of the system are:

1) where

$$r = r_o$$

$$-\lambda (2\pi r_o) \left(\frac{\partial T}{\partial r} \right)_{r=r_o} = \frac{(T(r, z, t) - T_f(z))}{\ln(r_w/r_o) + \frac{1}{2\pi \lambda_{sh}}} + \frac{1}{2\pi \alpha_w}$$

$$2) \text{ where } r = r_i, \left(\frac{\partial T}{\partial r} \right)_{r=r_i} = 0$$

$$3) \text{ where } z=0 \text{ or } z=l, \left(\frac{\partial T}{\partial z} \right)_{z=0,l} = 0$$

3. RESULTS AND DISCUSSION

According to 2-dimensional model of metal-hydride beds, the performance parameters and effect parameters can be analyzed by computer simulation. Some parameters of metal-hydride beds used in simulation can be shown in table 1.

Table 1. Parameters of metal-hydride beds used in simulation

Length	600m	Heat conduct coefficient	10 W/(m·K)
Innerradius	16mm	Filled density	6000g/(cm ³)
Outerradius	21mm	Mass of hydride filled	2kg
Thickness	5mm	High temperature of flow	425K
Volume	3e-4m ³	Low temperature of flow	310K

Results of 2-dimensional model of metal-hydride beds can be shown in table 2.

Table 2. Results of 2-dimensional model of metal-hydride beds

Cycle time(s)	770	COP	0.4
Refrigeration time(s)	450	Refrigeration power(w)	240
Mass of hydride(kg)	4		

From fig.2 radial temperature distribution where $z=l/2$ of metal-hydride beds (high temperature bed, low temperature bed) is presented when the process of refrigeration is over. Drop of temperature close to heat transfer flow is higher than that of far away with heat transfer flow. The main reason is that heat conduct of power of hydride is poor. In order to improve reaction velocity, heat conduct performance of power of hydride and metal-hydride bed should be improved, but without affecting mass transfer performance of hydrogen gas.

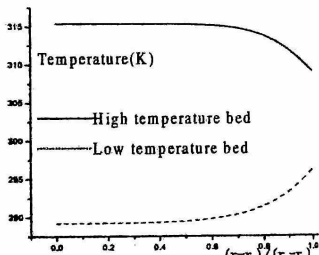


Fig.2 radial temperature distribution where $z=l/2$ of metal-hydride beds (high temperature bed, low temperature bed)

Fig.3 shows outer and inner temperature where $z=l/2$ of high temperature metal-hydride bed during the period of cycle time on the different heat conduct transfer coefficient 1W/(m·K) and 10W/(m·K). When heat conduct transfer coefficient is 10 W/(m·K), the

highest drop of temperature is 21K. When heat conduct transfer coefficient is 1 W/(m·K), the highest drop of temperature is 65K.

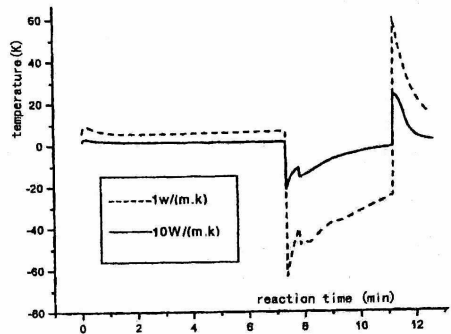


Fig.3 Outer and inner temperature distribution where $z=l/2$ of high temperature metal-hydride bed during the period of cycle time (action time)

Fig.4 shows outer and inner hydrogen gas concentration where $z=l/2$ of low temperature metal-hydride bed during the period of cycle time. The variation of inner hydrogen gas (far away with bed outer wall) is small. The variation of outer hydrogen gas (close to bed outer wall) is big.

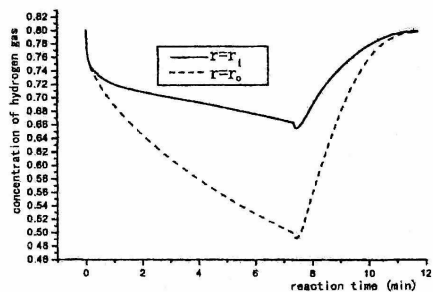


Fig.4 Outer and inner hydrogen gas concentration where $z=l/2$ of low temperature metal-hydride bed during the period of cycle time (reaction time).

Fig.5 and fig.6 shows axial temperature and concentration of hydrogen gas distribution where $r = (r_i + r_o)/2$ when the refrigeration process is over. Heat conduct transfer coefficient of metal-hydride bed is 10 W/(m·K). Variation of temperature and concentration of hydrogen gas along the axial are small. The main reason is that where r is same, heat transfer resistance between metal-hydride bed and heat transfer flow is almost same, while temperature

variation of heat transfer flow is small.

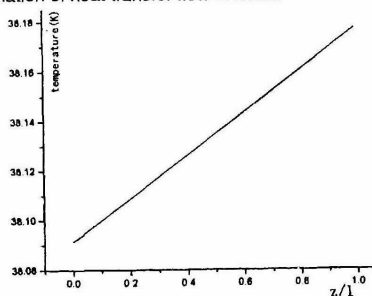


Fig.5 Axial temperature distribution where $r = (r_i + r_o)/2$ when the refrigeration process is over.

In order to observe the effect of heat conduct coefficient and thickness of metal-hydride bed on performance of the whole system, computer simulation is carried on different conditions. Heat conduct coefficient changed from 0.4 W/(m·K) to 11 W/(m·K). Thickness of metal-hydride bed changed from 3mm to 10mm.

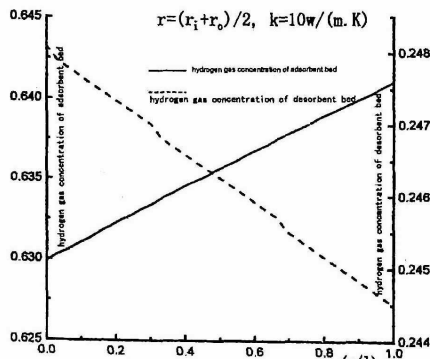


Fig.6 Axial concentration of hydrogen gas distribution where $r = (r_i + r_o)/2$ when the refrigeration process is over.

Fig.7 shows relationship between refrigeration power and metal-hydride beds when thickness of metal-hydride bed is 5 mm. With increasing of heat conduct coefficient of metal-hydride beds, refrigeration power increases. When heat conduct coefficient of metal-hydride beds is less than 3.5 W/(m·K), refrigeration power decreases obviously. It shows that improving performance of heat conduct is an important measure to improve performance of system.

Fig.8 shows relationship between refrigeration power per mass of hydride and thickness of metal-hydride beds. With increasing of thickness of beds, refrigeration power per mass of hydride decreases. It shows that decreasing the thickness of beds can improve performance of system.

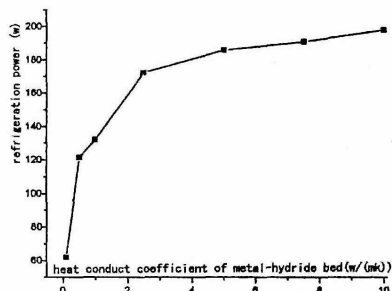


Fig.7 relationship between refrigeration power and metal-hydride beds when thickness of metal-hydride bed is 5 mm.

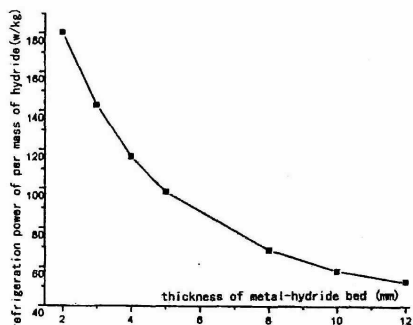


Fig.8 Relationship between refrigeration power per mass of hydride and thickness of metal-hydride beds.

4. CONCLUSIONS

From the results of computer simulation, we can see that 2-dimensional model of metal-hydride beds can help us study process of heat and mass transfer on metal-hydride beds. To improve performance of heat conduct of metal-hydride bed and decrease the thickness of metal-hydride bed wall are valid measures to improve the refrigeration coefficient of performance.

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