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Performance analysis of a single stage four bed metal hydride cooling system, part A: influence of mass recovery

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Abstract

The concept of mass recovery in metal hydride systems is studied with a single stage multi-bed cooling system as example. Mass recovery results in variation of bed temperatures due to removal or addition of heat of desorption or absorption respectively. Coefficient of performance and cold output increase while required heat input decreases for the mass recovery cycle. Thus mass recovery between hydride reactors is found to improve system performance compared to that of a basic system.

Keywords: Metal hydride; Mass recovery; Cooling system

1. Introduction

Metal hydride heating and cooling systems use hydrogen as working fluid. The simplest form of the heat pump consists of a pair of high and low temperature reactors, which replaces the condenser/evaporator of the conventional solid sorption cooling system. Hydrogen being a cryogenic fluid, does not condense at normal refrigeration temperatures.

The conventional wet absorption systems with solution circuit operate under steady state conditions producing continuous cold output. Here the solution heat exchanger is a heat recovery device exchanging heat between the hot solution from the generator and the cold solution from the absorber. It is well-known that this heat recovery significantly enhances the COP of the system. Due to the continuous flow of the refrigerant–absorbent solution, heat recovery is easily possible in wet absorption systems. However, in case of solid sorption systems, it is rather difficult to achieve heat recovery. Literature reveals that some attempts for heat recovery in conventional solid sorption systems have been made [1–5].

The two-reactor metal hydride cooling and heating system is not only intermittent but also does not provide any scope for heat and mass recovery. The four-reactor metal hydride cooling system provides scope for heat and mass recovery in addition to delivering continuous cooling. In the basic cycle, the sensible heating of the bed from intermediate temperature to heat source temperature is an additional system requirement while the sensible cooling of the bed from intermediate temperature to refrigeration temperature reduces the cold output. The performance of the multi-bed cooling system can be increased if these sensible heating and cooling needs are reduced.

Multi-bed adsorption systems with condensable refrigerants can recover heat even though the system configuration is complicated [1]. Studies by Zheng and Worek [2] have shown that the performance of a multi-bed system is superior to that of the two-bed system with regard to both the COP and the cooling capacity when the beds are connected by a heat transfer fluid loop.

Recovery of internal heat of reaction is a well-known method which has resulted in improving the system performance. In the system demonstrated by Neveu and Castaing [3], two beds are used along with evaporator and condenser in a double effect cycle, wherein the heat rejected by the high temperature bed during absorption is used to desorb ammonia from another bed at the intermediate temperature.

Studies on heat and mass recovery have been reported for solid sorption refrigeration systems employing the activated carbon–methanol pair [4] revealing that the cooling capacity can be significantly increased with mass recovery. First and second law analyses of the internal vapour recovery

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Nomenclature

A	high temperature metal hydride bed
B	low temperature metal hydride bed
COP	coefficient of performance
C	specific heat . . . . $\text{kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$
$f_{s,298}$	slope factor at 298 K (= 0.8)
H/M	atoms of hydrogen per molecule of metal alloy
ΔH	enthalpy of formation . $\text{kJ}\cdot(\text{mol of hydrogen})^{-1}$
k	rate of variation of f_s with temperature, $= -0.004$
M	molecular weight of alloy . . . . $\text{kg}\cdot\text{kmol}^{-1}$
m	mass of the bed . . . . kg
N	alloy atoms per mole (for AB_2, $N = 3$)
n	moles of hydrogen
P	equilibrium pressure of bed . . . . bar
Q	total heat . . . . $\text{kJ}\cdot(\text{kg of alloy } A)^{-1}$
q	sensible heat . . . . $\text{kJ}\cdot(\text{kg of alloy } A)^{-1}$
ΔS	entropy of formation . . . . $\text{kJ}\cdot(\text{mol of hydrogen})^{-1}\cdot\text{K}^{-1}$
T	temperature . . . . °C
X	concentration of hydrogen (atoms of hydrogen per molecule of alloy)

Subscripts

b	hydride bed
c	low temperature
f	final condition
H	hydrogen
h	high temperature
i	initial condition
m	intermediate temperature
mid	mid-point of the plateau
R	with mass recovery
W	without mass recovery
1	desorbing bed
2	absorbing bed

process have also been carried out for sorption systems with condensable refrigerants [5].

In the light of the above it is felt that mass recovery can be beneficial in the case of metal hydride systems also. A comprehensive study of mass recovery in the multi-reactor metal hydride cooling system is presented in this paper. The performance of the mass recovery cycle is compared with that of the basic cycle.

2. Operation of the systems

There are four possible mass recovery processes in the four bed cooling system. In case of mass recovery between A_1 and B_2, increase of hydrogen concentration in B_2 recovered from A_1 increases the pressure in the bed B_2. Therefore, the pressure difference between A_2 and B_2 decreases at the start of the next half cycle which reduces the amount of hydrogen transferred. Mass recovery from B_1 to A_2 decreases hydrogen concentration of B_1. This reduces the amount of hydrogen available for desorption from bed B_1 in the next half cycle when attached to a cooling load thereby decreasing the refrigerating effect. Similarly, mass transfer from B_1 to B_2 also reduces the refrigerating effect as hydrogen concentration in bed B_1 gets reduced. Hence mass recovery between A_1 and A_2 alone is considered in this paper as it has the potential to contribute to the system performance.

Fig. 1 shows the schematic of the metal hydride cooling system. Reactors A_1 and A_2 contain the high temperature alloy while B_1 and B_2 contain the low temperature alloy. Figs. 2 and 3 show the Van't Hoff plots for basic and mass recovery cycles respectively. The operation of the basic cycle is explained as follows (Fig. 2):

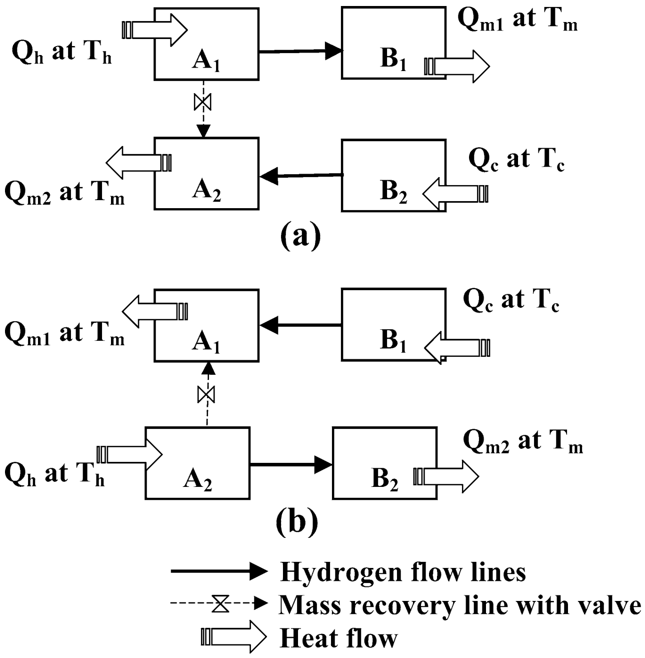

Fig. 1. Schematic diagram of the four bed single stage metal hydride cooling system: (a) First half cycle; (b) Second half cycle.

Step 1: Initial condition of A_1, B_1, B_2 and A_2 are represented by state points 1, 2, 3 and 4, respectively. A_1 is heated at T_h and B_1 is cooled at T_m to facilitate hydrogen transfer from A_1 to B_1 during which A_2 is cooled at T_m and its pressure falls below that of B_2 which is maintained at T_c. Thus hydrogen transfer also takes place from B_2 to A_2 which results in B_2 yielding the refrigerating effect at low temperature T_c. The concentration and pressure of