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Performance analysis of a single stage four bed metal hydride cooling system, part C: influence of combined heat and mass recovery

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Abstract

The effects of combined heat and mass recovery on the performance of a single stage multi-bed metal hydride cooling system is studied. A combined recovery cycle which effectively utilizes the advantages of both heat recovery and mass recovery is described. Reduction in sensible heating and cooling requirements along with increased hydrogen desorption results in improvement of coefficient of performance. Operating temperatures exert significant influence on the performance of combined recovery cycle. It is found that combined recovery is more effective at lower heat source temperatures and also at higher intermediate temperatures.

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Keywords: Metal hydride; Heat and mass recovery; Cooling system

1. Introduction

Thermally operated energy conversion systems have attracted renewed interest in recent times because of the possibility to utilize low grade heat energy to replace electric power. Among them, metal hydride based systems are probably the most promising ones. Harmful environmental effects of conventional cooling systems such as ozone depletion and global warming have also accelerated their growth. The application of metal hydride based systems ranges from storing hydrogen for use in automobiles, to energy conversion like heating or cooling. However, at present, metal hydride systems are less competitive than other heat operated systems because of their poor performance. Effective management of heat and mass transfer in the hydride beds is one possible means of improving the performance.

Recently, the authors have studied mass recovery [1] and heat recovery [2] in a single stage four-bed metal hydride cooling system. In conventional wet absorption systems with solution circuit, the weak solution-strong solution heat exchanger recovers heat between the hot solution from the generator and the cold solution from the absorber. This heat recovery significantly enhances the COP of the system. The cooling capacity and coefficient of performance of multi-bed absorption systems with condensable refrigerants such as ammonia have been proven to be higher than those of two-bed systems [3]. The internal heat of reaction can also be recovered in double effect systems to improve the system performance [4]. Studies on heat and mass recovery have also been reported for solid sorption refrigeration systems employing the activated carbon-methanol pair [5,6]. The main difference of metal hydride systems compared to conventional solid-sorption systems is that the working fluid (i.e., hydrogen) does not condense.

Realizing the fact that combined heat and mass recovery studies on metal hydride systems are not available in the literature, this paper aims to present the analysis procedure and to bring out the influence of the combined recovery on the performance of a single stage four-bed metal hydride cooling system. Results for the combined recovery cycle and comparison with mass recovery, heat recovery and basic cycles are presented.

2. Operation of the system

A schematic of the metal hydride cooling system with combined heat and mass recovery is shown in Fig. 1. Reactors A_1 and A_2 contain the high temperature alloy while B_1 and B_2 contain the low temperature alloy. The analysis and computational procedure of the basic cycle was

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Nomenclature

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

Subscripts

1	desorbing bed
2	absorbing bed
A	high temperature metal hydride bed
B	low temperature metal hydride bed
c	low temperature
f	final condition
H	hydrogen
h	high temperature
i	initial condition
int1	temperature of A_1, A_2 after heat recovery
int2	temperature of B_1, B_2 after heat recovery
m	intermediate temperature
mid	mid-point of the plateau
R	with combined mass and heat recovery
W	without combined mass and heat recovery

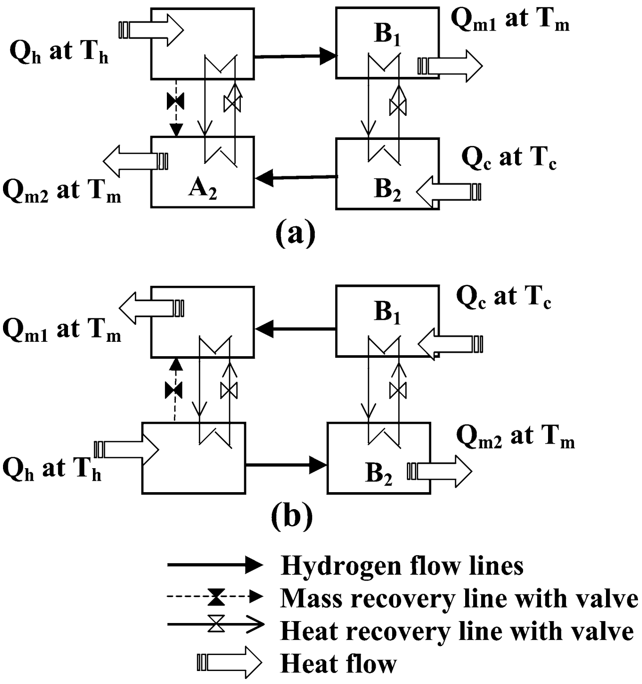

Fig. 1. Schematic diagram of the four bed single stage metal hydride cooling system: (a) First half cycle; (b) Second half cycle.

described recently by the authors [1]. The Van't Hoff plot for the combined recovery cycle is shown in Fig. 2.

Combined recovery cycle can be of two types in the four bed cooling system. In the first type heat recovery precedes mass recovery between A_1 and A_2 while in the other type, heat recovery succeeds mass recovery between A_1 and A_2. However, under ideal conditions, the former sequence is not possible because at the end of heat recovery, the pressure of A_2 is greater than that of A_1 [2]. Thus mass recovery between A_1 and A_2 cannot succeed heat recovery between the same beds. Therefore, a combined recovery cycle in which heat recovery succeeds mass recovery between A_1 and A_2 alone is considered in this paper as it has the potential to improve the system performance. The combined recovery cycle operates as follows:

Step 1: To start with, A_1 at T_h, B_1 at T_m, B_2 at T_c and A_2 at T_m are at state points 1, 2, 3 and 4, respectively. A_1 is heated by an external source while B_2 is connected to the cooling load. Hydrogen transfer takes place from A_1 to B_1 and B_2 to A_2. The concentration and pressure of A_1 and B_2 decrease while those of A_2 and B_1 increase. The desired cold output is thus obtained at low temperature T_c. At the end of this step, A_1, B_1, B_2 and A_2 are at state points 1′, 2′, 3′ and 4′, respectively.

Step 2: Reactors A_1 and A_2 are isolated from the external heat transfer circuits and connection is established between them by opening the hydrogen valve. Hydrogen transfer take place from the high pressure bed A_1 to the low-pressure bed A_2 till pressure equalization (P_1 in Fig. 2) occurs. The temperature of A_1 is reduced to T_1 due to removal of heat of desorption and the temperature of A_2 is increased to T_2 due to addition of heat of absorption. The heat of the transferred hydrogen also affects the bed temperatures. At the end of mass recovery, A_1 and A_2 reach state points 5 and 5′, respectively. The hydrogen valve between A_1 and A_2 is closed and the heat transfer fluid is circulated between A_1 and A_2 and also between B_1 and B_2. At ideal conditions, heat recovery can take place till the temperatures of beds A_1 and A_2, and also those of B_1 and B_2 are equalized. A_1 and

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