INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 41 (2016) 3961–3973

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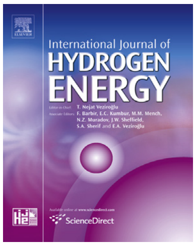

Effect of heat transfer enhancement on the performance of metal hydride based hydrogen compressor

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ARTICLE INFO

Article history:
Received 15 October 2015
Received in revised form
26 December 2015
Accepted 3 January 2016
Available online 25 January 2016

Keywords:
Metal hydride based hydrogen compressor
Heat transfer augmentation
Metal hydride pellets
Kinetics
Compression ratio

ABSTRACT

A single stage metal hydride based hydrogen compressor has been developed using $La_{0.8}Ce_{0.2}Ni_5$ hydride. The performance of the hydrogen compressor was evaluated in three different configurations to determine the effect of heat transfer augmentation. Two different types of metal hydride pellets were developed. Graphite flakes were mixed with $La_{0.8}Ce_{0.2}Ni_5$ hydride for the first type of pellets. While in the second type, an augmentation structure made with copper wire mesh was embedded with the mixture of $La_{0.8}Ce_{0.2}Ni_5$ hydride and graphite flakes. All the three types of $La_{0.8}Ce_{0.2}Ni_5$ hydride beds namely, with loose MH powder (LMHP), pellets of MH powder and graphite fibres (PMHGF), and pellets of MH, graphite fibres with embedded copper wire mesh structure (PMHGFCu) were tested for a wide range of pressure and temperature conditions and their performances were compared. As expected, the heat transfer enhancement of $La_{0.8}Ce_{0.2}Ni_5$ hydride bed resulted in enhancement of kinetics of hydrogenation/dehydrogenation and performance of hydrogen compressor. The maximum pressure ratio, maximum cycle efficiency, minimum time to reach saturation stage during absorption in cases of LMHP/PMHGF/PMHGFCu were 4.18/5.04/5.2, 5.1%/5.94%/6.07%, 400 s/250 s/220 s respectively. The highest increase in compression ratio and efficiency in case of pellets bed compared to those for powder bed were 76.51% and 29.3% respectively.

Introduction

Metal hydride based hydrogen compressor (MHHC) is one of the several applications of metal hydrides by the virtue of exothermic/endothermic reversible reactions of hydrogen absorption/desorption respectively [1]. The MHHC is a proven alternative to mechanical compressors owing to the disadvantages/limitations of the latter namely frictional losses, noise due to moving parts and requirement of high grade energy. The compression of hydrogen using MHHC has added advantage of safety and purity of hydrogen [2,3]. An MHHC comprises a metal hydride container (reactor), with a filter (to allow uniform distribution of hydrogen and to avoid the contamination of gas pipes with fine particles of MH), heat exchanging sources for maintaining two different temperatures and low pressure hydrogen supply source. The heat energy required for maintaining the higher temperature in the

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http://dx.doi.org/10.1016/j.ijhydene.2016.01.011

cycle can be obtained from renewable energy source or industrial waste heat. The compressor operates in a cycle consisting of following four processes [4].

Process 1–2: Hydrogen supplied at low temperature and low pressure is absorbed by the metal hydride.

Process 2–3: Sensible heating from low temperature T_a to high temperature T_d and consequent compression of hydrogen from P_s to P_d

Process 3–4: High pressure hydrogen is desorbed at high temperature T_d

Process 4–1: Sensible cooling from T_d to T_a

Parameters governing the performance of MHHC can be classified as either *material related* parameters or *operation/design related* parameters. Reversible hydrogen sorption capacity, heat of absorption/desorption (ΔH), specific heat (c_p), thermal conductivity and sorption hysteresis are some of the material related parameters. Heat transfer rate from/to MH container, void space of MH bed, bed thickness, hydrogen absorption/desorption temperatures, supply pressure of hydrogen, pressure ratio and hydrogen throughput are operation/design related parameters [3,4]. Several works focused on optimization of these properties and their effects on MHHC performance are reviewed thoroughly by Lototskyy et al. [3]. These parameters are interdependent and thus the efficiency of MHHC ultimately depends on combination of values of these properties. Nomura et al. [5] used hydride container made with copper tube elements embedded with aluminium fins and enveloped with stainless steel water jacket for their MHHC operating with 16.34 kg of $LaNi_5$ hydride. The compressor was reported to be capable of desorbing 360 l/min high pressure hydrogen. The industrial prototype of MHHC developed by E.P. Da Silva [2] incorporated three modules of MH beds with 1 kg of FeTi hydride in each module. The operation of these three modules was governed by a drive to achieve cyclic functioning of the compressor. Y. F. Shmal'ko et al. [6] coupled an $MmNi_5$ hydride based MHHC to a cryogenic compressor to get the output pressure of hydrogen as high as 4 kbar in a 30 cm^3 volume at room temperature. MHHC was used as the first stage compressor to give an intermediate hydrogen pressure of 40 MPa. Muthukumar et al. [7] studied the effect of variation of supply pressure and source temperature on $MmNi_{4.6}Al_{0.4}$ hydride based MHHC. Laurencelle et al. [8] utilized the heat released by an electrolyser (used as source of hydrogen production) as energy supply for a three stage MHHC. Kim et al. [9] analyzed the performance of MHHC with absorption temperature, desorption temperature and kind of metal hydride as variables. Hopkins and Kim [10] studied the characteristics of a dual stage MHHC both experimentally as well as through a finite time thermodynamics model developed by them. Table 1 summarizes the details of experimental works on MHHC.

The diffusion of hydrogen through the formed hydride phase is one of the rate limiting steps. The absorption and desorption rate of metal hydride beds also depends on the average temperature of the bed and pressure gradient available for absorption/desorption to occur. All the absorption and desorption kinetics equations proposed in the literature [11–15] consists of these parameters (temperature and pressure differential). Also numerous experimental and theoretical studies on heat and mass transfer aspects of metal hydride available in the literature [3,4,7,8,16,17] showed that the absorption and desorption rates are heat transfer dependent. The low value of effective thermal conductivity of metal hydride beds leads to poor heat transfer characteristics of the beds thereby causing slower absorption/desorption kinetics. Researchers have implemented many techniques for improving the heat transfer characteristics of MH beds for the application of MHHC. Nomura et al. used copper tubes embedded with aluminium fins as MH container [5]. While Shmal'ko et al. [6] incorporated transversal copper ribs having thickness of 0.5 mm with a pitch of 4 mm in the SS cylindrical MH reactor. Laurencelle et al. tried aluminium foam occupying 10% of internal volume of aluminium made MH reactor and gained a good enhancement of thermal conductivity of MH bed [8]. One of the techniques to improve the effective thermal conductivity of the bed is compacting the metal powder and using pellets instead of loose metal powder. In their experiments, Kim et al. [9] made pellets with copper coated MH powder. Thermal mass proportion of pellet was 41.5% and that of reactor was 56.2%. Hopkins and Kim [10] also followed the heat transfer augmentation method (micro encapsulation of copper and making pellets) used by Kim et al. [9] for their work. Kelly and Girdwood [18] had mixed appropriate quantity of aluminium with the hydriding metal alloy. Thus many experimental works reported in the literature proved that compacting increased the effective thermal conductivity of metal hydride beds, which leads to better heat transfer of the metal hydride beds and can improve the hydrogen absorption and desorption kinetics.

Talaganis et al. [19] developed and analyzed reduced and simplified lumped models of cyclic processes of MHHC. The simplified models were claimed to show an excellent match with the experimental and numerical results while drastically reducing the computation time and energy. A mathematical model developed for predicting the performances of a three stage MHHC adopted energy, momentum, mass conservation and reaction kinetics equations as governing equations and these equations were solved simultaneously using finite volume method. The model predicted a maximum pressure ratio of 28 for supply conditions of 20 °C and 2.5 bar for the three stage MHHC [20].

From the literature two points are observed; firstly, for improvement of heat transfer characteristics of MH beds, either high thermal conductivity material structure or compaction techniques have been implemented, a combination of these two has not yet been attempted. Secondly, although the arrangements were made for improvement of heat transfer characteristics of MH bed but the relative effect of these improvements have not been analyzed experimentally. This paper aims at comparing the performance of MHHC using $La_{0.8}Ce_{0.2}Ni_5$ hydride on the basis of heat transfer improvement techniques. Three different hydride bed configurations, LMHP, PMHGF and PMHGFCu were used for comparison.

Experimental set up and procedure

The schematic arrangement of experimental setup used in the present work is shown in Fig. 1. The gas flow lines were fabricated with ¼ inch seamless SS 316 tubes, PTFE flexible