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Performance analysis of cylindrical metal hydride beds with various heat exchange options

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ABSTRACT

A 3D numerical heat-and-mass transfer model was used for the comparison of H_2 uptake performances of powdered cylindrical MH beds comprising $MmNi_{4.6}Al_{0.4}$ hydrogen storage material. The considered options of heat exchange between the MH and a heat transfer fluid included internal cooling using straight (I) or helically coiled (II) tubing, as well as external cooling of the MH bed without (III) and with (IV) transversal fins. The dynamic performances of these layouts were compared based on the numerical simulation. The effect of heat transfer coefficient was also analysed.

1. Introduction

Metal hydrides (MH) have the ability to reversibly absorb and desorb relatively large amounts of hydrogen in wide ranges of temperatures and pressures. They have many potential applications including hydrogen storage, hydrogen compression and related thermal management systems (heat storage, pumping and upgrade) [1–5].

Hydrogen absorption in MH is an exothermic reaction when the generated heat has to be effectively removed to achieve the desired H_2 charge rate. Similarly, the endothermic H_2 desorption needs supply of the heat to MH. Thus, the performance of any MH based thermal device is essentially determined by heat transfer processes, and the thermal management of a hydrogen storage container (MH tank) is very important.

In recent years, many researchers have made numerous attempts to improve the heat transfer in the MH reactors, by enhancing the effective thermal conductivity of the reaction beds [6–9] and incorporating heat exchangers [10,11]. Kim et al. [6] presented the experimental results for the coupled metal-hydride reactors comprising $Ca_{0.4}Mm_{0.6}Ni_5$ (Mm = Mischmetal) with hydrogen pumped by the compressor. In order to augment heat transfer in the reactor, the MH powder particles were copper-coated and compressed into porous MH compacts. Botzung et al. [8] presented a hydrogen storage tank using MH for a combined heat and power system. During H_2 absorption/desorption, the heat was dissipated/supplied by fluid circulation. An integrated plate-fin type heat exchanger was designed to obtain good capacity and to reach high absorption/desorption rates.

In effect, incorporating heat exchangers into MH reactors has been proven to be an effective way to enhance the heat and mass transfer, thus improving hydrogen storage performance. Recently, employing 4 kg of $Ti_{1.1}CrMn$, Visaria et al. [12,13] studied the hydriding performance of MH reactor with coiled tube heat exchanger and modular tube – fin heat exchangers but they tested the MH reactor at higher pressures, from 70 to 330 bar. The aforementioned research was mainly focused on the MH reactors equipped with a straight pipe heat exchanger. In order to further enhance the heat transfer and improve the hydrogen storage process in MH reactors, more attention has been paid to the reactors incorporating helical coil heat exchanger, which has the superior effect on the enhancement of heat and mass transfer due to its secondary circulation [14].

Minko et al. [15] studied heat-and-mass transfer in an MH bed of cylindrical geometry for thermal-sorption hydrogen compression. The numerical model was verified on $LaNi_5$ at the operating conditions from 4 atm/20 °C (H_2 absorption) to 40 atm/150 °C (H_2 desorption). There was also analysed the effect of introduction of aluminium framework in the MH powder on the H_2 absorption/desorption dynamic performance. It was shown that the aluminium framework allowed to increase the thickness of the MH bed in three times without compromising H_2 charge/discharge dynamics.

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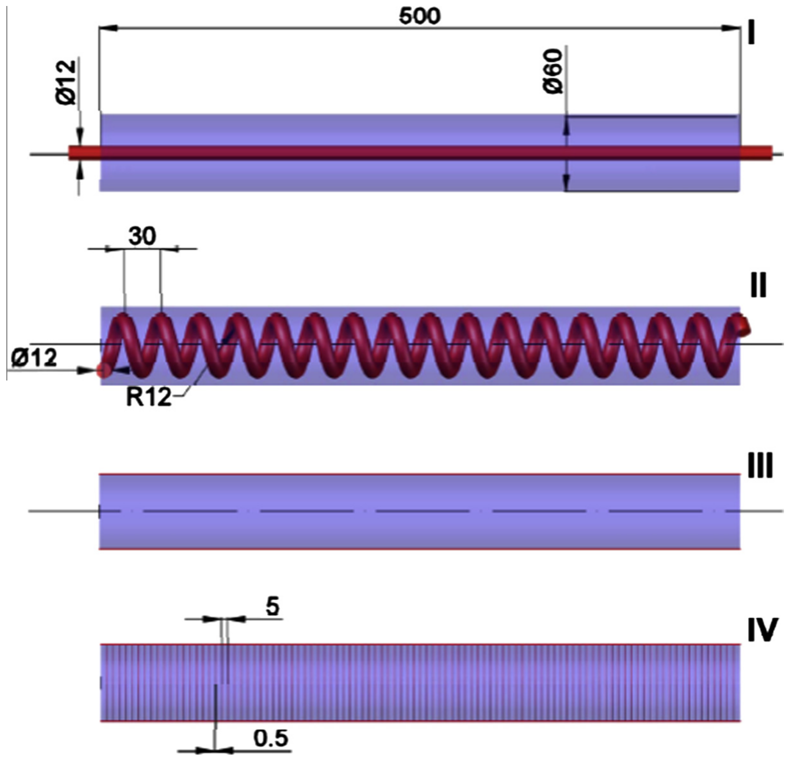

Fig. 1. Schematic drawings of metal hydride bed: I –internal cooling/axial heat exchange tube, II – internal cooling/coiled heat exchange tube, III – external cooling, and IV – external cooling/transversal heat distribution fins.

A key issue in the development of any gas phase MH application is the selection of optimal layout of the MH tank which, from the one hand, should fit in space and weight constrains of the end-user, and, from the other, has to provide fast H_2 charge/discharge dynamics at the required hydrogen storage capacity and minimal costs. The acceleration of the H_2 charge/discharge, first of all, depends on the intensity of the heat exchange between a heat transfer fluid (HTF) and the MH [5]. Apart from the methods of augmentation of the bed heat transfer overlooked above, a general system layout at similar bed sizes and geometries is very important for the optimisation. As a first optimisation step, a proper comparative modelling of various heat exchange layouts has to be carried out at the similar conditions. Despite of numerous modelling activities [8,10,12–19, etc.], there is a lack of such a comparison in the literature.

In the present study, a 3D numerical model of heat-and-mass transfer in MH beds has been developed using typical simulation approaches [16,17]. The model has been further applied for the comparison of hydrogen uptake performance for cylindrical MH beds with four MH cooling layouts: straight pipe (I) and helical coil (II) internal heat exchangers, and external cooling of the MH powder without (III) and with (IV) transversal fins. The selected layouts are simple for manufacturing and MH powder loading. All reactors contained the same AB_5 type hydrogen storage material. The selected external dimensions of the modelled MH beds were close to typical size of MH containers for on-board hydrogen storage and supply system for hydrogen-fuelled utility vehicle (forklift).

2. Summary of modelling details

Fig. 1 shows the model of four MH beds discussed in this paper. The considered options of heat exchange between the MH powder and the HTF included (I, II) internal cooling using straight (I) and helically coiled (II) tube, as well as (III, IV) external cooling of the MH without (III) and with (IV) transversal fins (copper, 0.5 mm thick, 5 mm pitch).

The main characteristics of the MH beds considered in the present work are presented in Table 1. For the correct comparison, the MH bed was assumed to have the same dimensions (60 mm in diameter and 500 mm in length) in all four cases, and the MH loading density[1] (4031 kg/m^3, or about 48% of the alloy density, see Table 2) was also assumed to be the same. As it can be seen from Table 1, the main difference between the internal (I, II) and the external (III, IV) cooling is the area of the heat exchange between the MH and the HTF (I < II < III = IV). The smaller differences are in the MH material volumes resulting in the decrease of hydrogen storage capacity from ~8% (I and IV) to ~24% (II) as compared to case III where whole volume of the MH bed is occupied by MH powder.

The simulations were performed using COMSOL Multiphysics, versions 4.2 and 4.4.

The exact mathematical formulation of heat and mass transfer mechanism within the MH bed is difficult due to the influence of numerous factors most of which are related to the properties of the used MH material. The assumptions made for the simplified treatment of the problem are listed below.

1. Hydrogen is treated as an ideal gas as the pressure within the bed is moderate.
2. The solid and the gas are at the same temperature (local thermal equilibrium).
3. Effect of radiative heat transfer is negligible. This assumption is valid for all hydride forming alloys whose operation temperatures are well below 100 °C.

[1] We assumed the MH loading density to be equal to 60% of the density of the material in the hydrogenated state that is the maximum safe limit of filling the MH containers [5]. The value of 4031 kg/m^3 is close to the effective MH density (4200 kg/m^3) assumed in [16].