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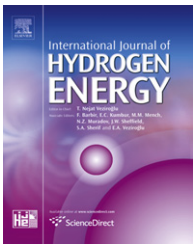

On the selection of metal foam volume fraction for hydriding time minimization of metal hydride reactors

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ABSTRACT

Here we examine how the hydriding time of a metal hydride reactor (MHR) varies with the volume fraction, φ_{mf}, of a metal foam installed in the reactor. Technically, an experimentally validated mathematical model accounting for the hydrogen absorption kinetics of $LaNi_5$ is used to compute the heat and mass transport in a cylindrical MHR. We then demonstrate that, with a fixed amount of metal hydride powder sealed in the reactor, saving a relatively small fraction (say, 1%) of the MHR internal volume to accommodate a metal foam usually suffices to substantially facilitate heat removal from the reactor, thereby greatly shortening the MHR hydriding time. However, for a metal foam of fixed apparent size, increasing φ_{mf} would reduce the metal hydride content, and hence the maximum hydrogen storage capacity, of the MHR. Consequently, if a prescribed amount of hydrogen is to be stored in the MHR, the hydriding time would decrease with increasing φ_{mf} at first (due to heat conduction augmentation), reach a minimum at an "optimal" φ_{mf} value, and then increase drastically due to metal hydride underpacking.

1. Introduction

In the development of hydrogen power systems, fuel (hydrogen) storage and transportation are an important issue. Currently, because of its relatively high hydrogen storage capacity and safety implications, hydrogen storage in metal hydrides appears to be a promising option [1]. In practice, a hydriding intermetallic compound is pulverized into powder form (to increase the reaction surface area per unit apparent volume), and then sealed in a metal hydride reactor (MHR), which usually takes the shape of a cylindrical container [2,3]. As hydrogen absorption and desorption of metal hydrides involve heat release and consumption, respectively, thermal management of an MHR strongly affects its hydriding/dehydriding time, and therefore is an important issue in MHR design and optimization [4,5]. Meanwhile, the hydriding/dehydriding process in an MHR is further complicated by the gaseous hydrogen flow through the porous metal hydride bed. (Other key issues in the technical design of MHRs are discussed recently by Yang et al. [6]).

Due to the synergetic interactions of the aforementioned factors, the performance of an MHR is highly sensitive to its operating conditions (such as the heat transfer fluid temperature [7–9] and reactor inlet/exit pressure [9–11]). Also, thermal management of MHRs presents some practical challenges, since metal hydride powders typically have low effective thermal conductivities (on the order of 0.1 W/m-K [12]). Various methods of heat conduction augmentation therefore have been proposed for MHRs. Basically, such methods can be classified into two categories [13], namely using extended surfaces (in the forms of fins, foams, or meshes; see [13–15] for example) and binding metal hydrides into a solid matrix formed by a high-conductivity material (such as copper, aluminum, or nickel [14,16–18]). Recently, to

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further facilitate MHR heat removal, Mellouli et al. [19] inserted a spiral heat exchanger (and a finned spiral heat exchanger instead in a follow-up work [20]) in an MHR, and demonstrated that the hydriding time can be significantly reduced. (Note, however, that when the hydriding and dehydriding processes are mass transfer controlled, instead of heat transfer controlled, the MHR performance may not be improved as significantly by sophisticated thermal management strategies [21]).

The present work is motivated by recent studies on the use of metal foam in MHRs. Specifically, on the basis of a one–dimensional (1-D) model, Laurencelle and Goyette [22] demonstrated that the hydriding and dehydriding times of an MHR can be substantially reduced by installing an aluminum foam in it. (In the 1-D model, all system state variables depend on time and the radial coordinate only.) A particularly impressive finding was that, when an aluminum foam of 9% volume fraction (or 91% porosity) is used, the reactor diameter can be increased by a factor of 7.5 while maintaining a reaction rate similar to that of a smaller reference reactor (which does not contain an aluminum foam). In other words, it is possible to achieve a 50-fold increase in hydrogen storage capacity (per unit reactor height) by installing an aluminum foam in a larger reactor (instead of using the smaller plain reactor) without increasing the hydriding and dehydriding times. Some of their model predictions were validated by comparison with experimental data. Meanwhile, Mellouli et al. [23] extended the 2-D model of Jemni et al. [24] to account for the presence of a metal foam in an MHR. They then studied numerically how the thermophysical properties, pore density, and pore size of a metal foam (with the technical data for Duocel® aluminum foam [25]) affect the hydriding time of an MHR containing the metal foam.

In the works cited above, the effectiveness of using metal foam for improving the MHR performance through heat conduction augmentation has been clearly demonstrated. However, it appears that such works did not examine the effects of the metal foam volume fraction (φ_{mf}, which is the ratio of the net volume occupied by the metal material to the apparent volume of the foam as a whole) on the overall MHR performance. This issue is worth addressing for the reason that, while the presence of a metal foam improves heat conduction in an MHR, it also reduces the amount of metal hydride powder that can be sealed in the MHR to store hydrogen. So, for an MHR to achieve a certain hydrogen storage capacity, there may exist an "optimal" choice of φ_{mf} value, and here we wish to explore such a possibility.

To serve this purpose, however, a slightly more comprehensive theoretical model than that cited above is needed. Briefly, the spatial variation of hydrogen pressure in the MHR was taken into account by Mellouli et al. [23], but was neglected in the model of Laurencelle and Goyette [22]. Meanwhile, both models did not explicitly consider the dependence of the hydrogen flow resistance on the metal foam volume fraction. As the spatial non-uniformity of hydrogen pressure distribution in larger MHRs may be significant enough to affect the hydriding/dehydriding kinetics, here we shall basically follow the model of Mellouli et al. [23], but attach to it certain additional components to allow for a tunable metal foam volume fraction. Meanwhile, to expedite computations, we shall also make the 1-D approximation like that in Laurencelle and Goyette [22]. The modified model will be explained in Section 2, and the numerical method for its solution will be discussed in Section 3. After validating our modified model by comparing its numerical results with the experimental data of Laurencelle and Goyette [22] in Section 4.1, we shall discuss a series of

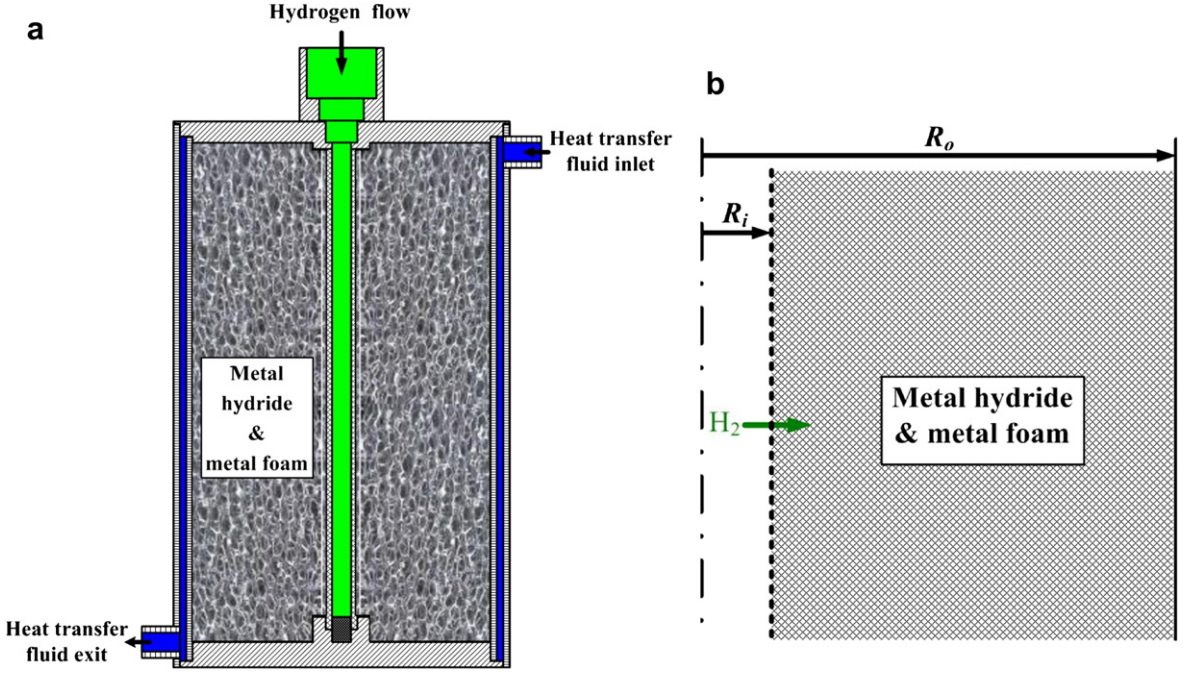

Fig. 1 – (a) Schematic of a cylindrical MHR within which a metal foam is installed; (b) the simplified 1-D computational domain.