PERFORMANCE OF A METAL HYDRIDE HYDROGEN STORAGE SYSTEM

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Introduction

Hydrogen is considered to be the ultimate fuel for the future, not only because of its renewable and nonpolluting nature, but also because water is the only byproduct during combustion. However, there are many roadblocks to the implementation of the hydrogen economy, such as the lack of refueling and storage infrastructures. Hence, a considerable effort is being put fourth worldwide to alleviate some of these roadblocks. For example, the Savannah River Technology Center (SRTC) has developed a novel metal hydride hydrogen storage container for niche transportation applications. In fact, despite their low gravimetric density, metal hydrides as a means to store hydrogen have been under consideration for many years because they have the ability to store hydrogen reversibly in the solid state at relatively low pressures and ambient temperature.

However, a metal hydride hydrogen storage container can be complicated and may contain heat transfer tubes as well as a heat transfer medium to overcome the enthalpic effects during charge and discharge. The SRTC container is an excellent example. It contains aluminum foam and a u-tube heat exchanger for heat transfer, it is only three-fourths filled with metal hydride powder to compensate for expansion during hydrogenation, and the sintered metal feed tube runs axially along the top of the container to ensure a uniform flux of hydrogen into the vessel. These complications present quite a challenge to the development of a mathematical model that can be used for design and optimization. To this end, experimental data are needed over a wide range of hydrogen charge and discharge conditions to calibrate and/or validate such a mathematical model.

Therefore, the objective of this paper is to present some of the results from a simple two level fractional factorial design study that reveals the effect of seven factors on the discharge performance of the SRTC hydrogen storage container from only sixteen different experimental runs. These results are used to further test the models developed previously under diverse operating conditions. Select experimental and modeling results are presented to show how a relatively simple model is able to capture the dynamic discharge behavior of a complex hydrogen storage container.

Table 1. Fractional Factorial Study Operating Conditions

<table>
<thead>
<tr>
<th>Factors</th>
<th>Factor Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Insulation</td>
<td>No, Yes</td>
</tr>
<tr>
<td>Water Flow Rate (gpm)</td>
<td>2, 4</td>
</tr>
<tr>
<td>Water Temperature (°C)</td>
<td>25, 55</td>
</tr>
<tr>
<td>Initial Bed Temperature (°C)</td>
<td>25, 55</td>
</tr>
<tr>
<td>Initial Bed Pressure (atm)</td>
<td>12, 20</td>
</tr>
<tr>
<td>H₂ Discharge Flow Rate (SLPM)</td>
<td>10, 30</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>No, Yes</td>
</tr>
</tbody>
</table>

Experimental

Seven process factors were identified as the critical factors for this study. They are the container insulation (In), u-tube water flow rate (Qw), u-tube water temperature (Tw), initial bed temperature (Ti), initial bed pressure (Pi), hydrogen gas flow rate (Qg), and hysteresis (Hy). These factors and their high and low levels are given in Table 1. The conventional “study one factor at a time” approach was inefficient here as it is incapable of quickly assessing the relative importance of each factor and how it interacts with the other factors. At the same time, a full factorial design for these seven factors was also impractical, as it would take considerable time to carry out 128 experiments. Hence, a two-level resolution IV fractional factorial design (1/8th fraction) comprising 16 runs was devised for these factors. The experiments were carried out as described elsewhere.

Results and Discussion

To understand the effects of these factors on the discharge performance of this container, several performance indicators or response variables of practical relevance were identified. However, due to space constraints, only a couple of them are discussed here. To isolate the factors or factor interactions that have significant effects, normal probability plots and Pareto charts were constructed for each response variable using MINITAB. The results for the time until the discharge flow rate is constant, and for the standard volume of H₂ discharged are shown in Figures 1 and 2.

![Figure 1. Normal probability plot and Pareto Chart for the estimated effects of the time until the discharge flow rate is constant.](image1)

![Figure 2. Normal probability plot and Pareto Chart for the estimated effects of the standard volume of H₂ discharged.](image2)
The time duration for which the molar flow rate stays constant is an important variable for assessing the performance of the hydrogen storage system as it provides information on how long the bed can be operated at the desired flow rate. Figure 1 shows the effects of the factors and the factor interactions for an alpha value of 0.10, which corresponds to a 90% confidence level. The only factor that had any significant effect was the hydrogen gas discharge flow rate.

The standard volume of hydrogen discharged, which also represents the bed capacity, is important for knowing how much hydrogen can be stored in the solid state and taken out during discharge. This quantity was based on the volume discharged up until 20% of the set value was reached. From Figure 2 it is evident that the factors influencing this variable were the initial pressure (Pi), initial temperature (Ti) and interaction between insulation (In) and gas flow rate (Qg). Since this was a resolution IV fractional factorial design, two-factor interactions were confounded with each other. Hence, In-Qg had an alias with two other factor interactions, namely Qw-Hy and Ti-Pi, and since real interaction effects are not likely to occur unless at least one of the factors involved in the interaction has a main effect, it was safe to assume that the alias structure of the two-factor interaction was dominated by the interaction between Ti-Pi, as they both occurred as significant main effects.

**Mathematical Model Simulations**

The models developed in a previous work were calibrated with a standard discharge run to obtain the heat and mass transfer coefficients; it was then used to predict other experimental runs at different hydrogen gas discharge flow rates. The same set of heat and mass transfer coefficients was able to predict the performance of all the runs with the same, reasonable accuracy. However, to understand the real potential of these models, they need to be tested under diverse conditions, such as used in this fractional factorial study. Thus, 8 runs, all corresponding to the insulation on condition, were used to test various models under very diverse conditions.

Figure 3 shows the predictions from several models for one of the runs from this study under extreme conditions. Here, the water flow rate was kept at its high value, while using hot water as the heat exchanger fluid. The initial bed temperature, pressure and discharge flow rate were also set at their high levels; and the hysteresis “yes” condition was used (recall, however, that its effect was insignificant). The predictions from the axial model with the same value of heat and mass transfer coefficients obtained from the previous study (132.4 W/m²/K) resulted in poor predictions; the value of heat transfer coefficient had to be adjusted to 41.625 W/m²/K to obtain a good fit. Nevertheless, the axial flow, radial energy (AFRE) model, using the same value of the bed conductivity (2.78 W/m/K) from the previous work, was able to predict the pressure discharge characteristics with reasonable accuracy. However, these predictions were improved by making the bed conductivity a linear function of loading. This trend was also evident in the temperature histories, where the variable conductivity model gave the best predictions among all the models.

Similar results were observed for another experimental run obtained at extreme conditions, as shown in Figure 4. The water flow rate was again high, but cold water was used as the heat exchanger fluid. The initial bed temperature and pressures were set at the low values, and the discharge flow rate was set at the high value. Again, the hysteresis “yes” condition was set. This time the old value of the heat transfer coefficient was able to predict the discharge characteristics. Typically, the lower value of 41.625 W/m²/K was needed when hot water was used, and the value of 132.4 W/m²/K was needed when cold water was used. Just like the previous case, the AFRE model with the same value of the bed conductivity predicted the pressure discharge curve with reasonable accuracy, which was further improved with the variable conductivity model. The temperature curves followed a similar trend. The AFRE predictions were good but they did not capture the characteristic dip in temperature just before the bed became exhausted. Interestingly, the variable conductivity model did capture this dip, at least qualitatively. Similar trends were observed with all the other experimental runs from this fractional factorial design study.

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**References**