OPTIMIZATION OF SPACING BETWEEN STAGGERED METAL HYDRIDE TANKS INTEGRATED FUEL CELL SYSTEM

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ABSTRACT: The sufficient hydrogen flow for requirements depends not only on the quantity contained in the metal hydride tanks, but also on other dynamic factors such as the ambient conditions, metal hydride kinetics and heat transfer mechanisms. In this study, the effects of dynamic factors on optimum spacing between metal hydride (MH) Hydrogen storage tanks are researched theoretically. A new approaching is presented for defining the optimum spacing between tanks according to different operating conditions. As MH alloys, AB5 type alloy (LaNi5) is selected. The analysis takes into account the effect of dynamic factors. The spacing is calculated by maximizing the heat transfer by means of accurate correlations. The results show that there exists an optimum spacing between the MH tanks for which the heat transfer is maximum and it should be considered to size the MH-Fuel cell system without extra cost.

Keywords: Hydrogen Storage, Metal Hydrides, Forced Convection

INTRODUCTION

Hydrogen storage systems must be efficient in order to show advantages of fuel cells. The hydrogen storage methods are generally classified into compression, liquefaction, metal hydride. Metal hydride is regarded as more convenient than the other Hydrogen storage methods. It has the advantages of safety, hydrogen storage capacity and reliability. Metal hydride process involves exothermic and endothermic reactions according to charging/discharging and requires thermal management for controlling process temperatures and enhancing process efficiencies. Thermal management is important for effective using of Hydrogen in Metal Hydride tanks. To supply sufficient hydrogen from tank to fuel cell system, the heat transfer capability has to be improved. Because thermal poorness is a serious disadvantage of the metal hydride, thus optimal design of the metal hydride tank is a crucial issue in relevant studies. Many researchers have established mathematical models to analyze heat and mass transfer characteristics of metal hydride tanks. Jemni and Nasrallah (1995) formulated a mathematical model for the two-dimensional transient heat and mass transfer within a metal hydride tank. Aldas et al. (2002) studied heat and mass transfer in a metal hydride bed. Bao et al. (2013) developed a model optimize the design parameters of the metal hydride tank. Cho et al. (2013) presented a modeling to simulate and control the dynamic processes of hydrogen discharge from a metal hydride tank in various operating conditions. Minko et al. (2014) presented to analyze heat and mass transfer processes in porous medium. Ma et al. (2014) presented the optimization of heat transfer fins for a finned multi-tubular metal hydride tank and derived the heat transfer equations of tank with various configuration fins (radius, thickness and number). Nakano et al. (2015) developed a metal hydride tank with the aim of recovering the reaction heat of a metal hydride with double coil type heat exchanger.

Dhaou et al. (2011) investigated heat transfer characteristics of a Metal hydride vessel based on spiral heat exchangers with and without fins. Raju and Kumar (2012) presented a systematic study to o optimize the heat exchanger design that influences the storage capacity, gravimetric hydrogen storage density, and refueling time for automotive on-board hydrogen storage systems. Satya et al. (2015) developed a 3D numerical model of heat-and-mass transfer in MH beds for the comparison of hydrogen uptake performance for four 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. Also, many studies on the performance analysis of a metal hydride subsystem which serves as a part of an integrated fuel cell system have been demonstrated by researchers. Førde et al. (2009) experimentally investigated hydrogen supply capacity of a metal hydride storage unit which is thermally integrated with a fuel cell. Rizzi et al. (2015) focused on development of the metal hydride tank and to its integration with the fuel cell for improving heat exchanges between the thermal fluid and the tank. Tetuko et al. (2016) presented a mathematical model to study opportunities for simultaneous passive thermal management of an integrated PEM fuel cell and metal hydrogen (MH) storage system by thermal bridging of these two components, using heat pipes. Jiang et al. (2005) studied the dynamic behavior of a thermally coupled hydrogen storage and fuel cell system using experimentally validated models of a metal-hydride hydrogen storage system and a proton exchange membrane (PEM) fuel cell stack.

Although the metal hydride hydrogen storage have been intensively researched, only that developed by Hilali (2015) investigated effect of arrangements of tanks on discharge performance in natural convection. Therefore, the placement of Metal Hydride tanks in the Fuel system have to optimize according to demand of hydrogen. The optimization was based on correlations to find optimum spacing and purpose was either maximum heat transfer or optimum volume. Generally, such the optimization technique is used to remove electric power dissipated in the electronics (Stanescu G, Fowler AJ, Bejan A.,1996).

Thus, this study presents a mathematical model that optimizes arrangements of staggered MH tank banks in forced convection according to different conditions. In the next sections, we give a detailed description of the mathematical model and results.

MATHEMATICAL FORMULATION

Figure 1 shows the arrangement bank of tanks and location in volume LxHxW. L, H and W are the length, height and width of the array, respectively. Tanks were assumed filled with $LaNi_5$ alloy. Reaction kinetics and thermophysical property data for $LaNi_5$ are readily available in literature. In the first step, the governing equations and a new approaching is presented for defining the optimum spacing between tanks according to different operating conditions. Analyses are carried out for various ambient temperatures (290 K, 300 K and 310 K), equilibrium pressures (60 kPa, 100 kPa and 120 kPa) and Reynolds Numbers (6000, 12000 and 30000). Forced convection heat transfer (q) occurs between the tank surfaces (Tw) and the surrounding fluid reservoir ($T\infty$).

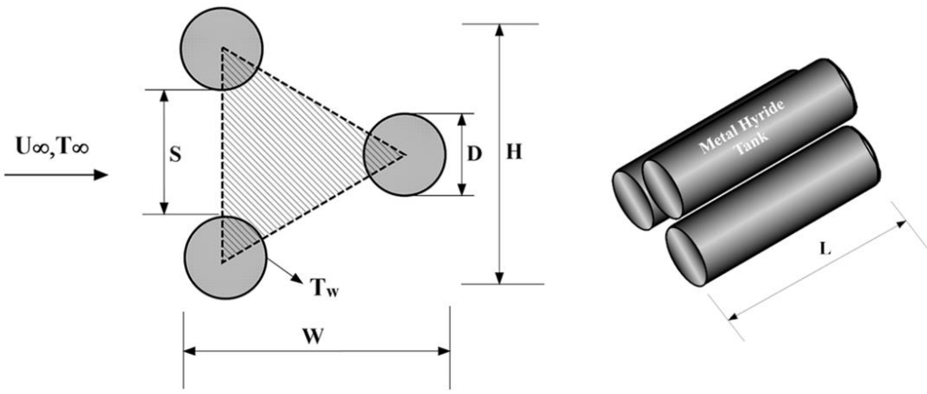

Figure 1. Configuration of the Horizontal Metal Hydride Tanks

In order to simplify the problem, the some assumptions made such as:

Both fluid flow and heat transfer are steady.
The fluid is single phase and incompressible.
Tank surface temperature is uniform.
All the surfaces of the tanks expose to surroundings except bottom and top of tanks.

The governing equations used in this study are described in the following. The equilibrium pressure of desorption is calculated using the van't Hoff relationship. The PCT of various representative AB_5 alloys are shown in Figure 2 (Sandrock 1996).

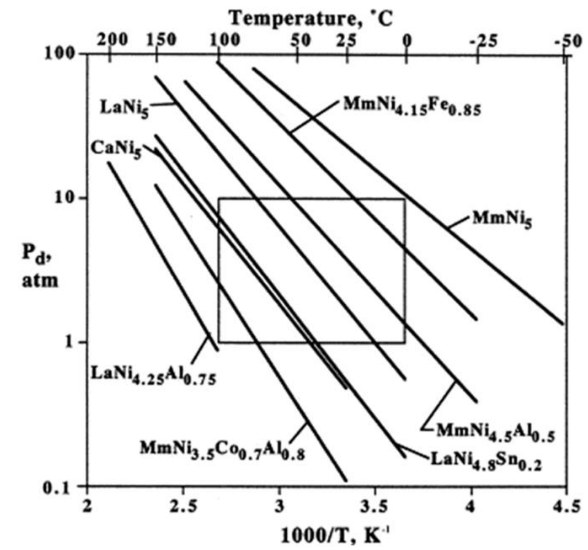

Figure 2. Van't Hoff Plots For Various AB_5 Hydrides

For the $LaNi_5$ hydrogen system, the evolution of the equilibrium pressure is given as a function of temperature.

$$\ln P_{eq} = A - \frac{B}{T} \qquad (1)$$

where A and B for Peqa are determined from the Hydride Material Listing Database as A = 17.608 and B =3704.60, and A and B for Peqd are determined as A = 17.478 and B =3704.60 [4].

The formulation consists of two steps . In the first step, we identify to extremes:

For large spacing, the heat transfer from one tank is

$$q_1 \cong \frac{k}{D} Nu_D \pi D L (T_w - T_\infty) \qquad (2)$$

Where Nusselt number is determined using the correlation due to Zukauskas (Incopera FP., 2007) :

$$Nu_D = 0{,}71 \cdot Re_D^{\,0{,}6} \cdot Pr^{0{,}36} \qquad Re_D \geq 10^3 \qquad (3)$$

Where Pr is the Prandtl number of the air stream, and The Reynolds number, Re_D, is determined as follows:

$$Re_D = \frac{U_{max}.D}{\nu}, \; U_{max} = \frac{(S+D)}{S}.U_\infty$$

Where is the maximum velocity for the staggered configuration and υ is the kinematic viscosity which is obtained depends on the film temperature ($T_f = (T_w - T_\infty)/2$).

The total number of tanks in the bank of cross- sectional area H x W is

$$n = \frac{H\,W}{(S+D)^2 \cos 30} \qquad (4)$$

According to Eq. (4), the total heat transfer from the bank of cross- sectional area H x W is

$$q_{large} = q_1 * n \quad (5)$$

$$q_{large} \cong 2{,}58 \frac{HLW}{(S+D)^2} k(T_w - T_\infty)\left\{ Re_D^{\,0,6} \cdot Pr^{0,36} \right\} \quad (6)$$

For small spacing, we are assuming tanks almost touch. The heat transfer from the array to air is, therefore, equal to the enthalpy gained by the air, which can be expressed by Eq. (7):

$$q_{small} = \dot{m}\, c_p (T_w - T_\infty) \quad (7)$$

where $\dot{m}$ is the mass flow rate through the L x W plane. The total heat transfer through the plane can be written now as:

$$q_{small} \cong \frac{1}{25} \rho . C_p . v . \frac{W.L}{H} . Re_D^2 . \left(S/D \right)^3 . (T_w - T_\infty) \quad (8)$$

In the second step, we determine optimum spacing S_{opt} for maximum heat transfer by setting as follows. Eq. (6) is equated to Eq. (8) to get the optimum spacing:

$$q_{large} = q_{small}$$

As shown Figure 3, the idea of intersection of asymptotes was utilized to show the existence of an optimum spacing for maximum rate of heat transfer. This technique was used by Bejan et al. 1984 and by Sadeghipour and Pedram Razi, 2001.

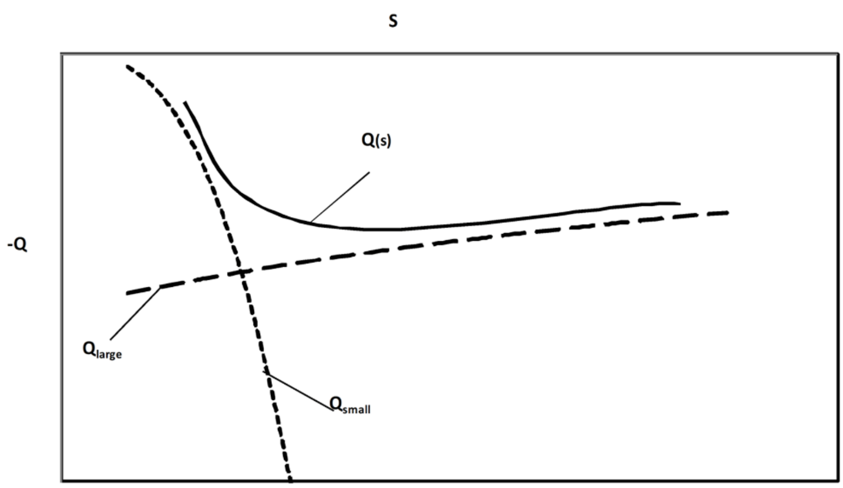

Figure 3. The Optimum Spacing As the Intersection of the Q_{large} and Q_{small} Asymptotes

The following optimum spacing formula is obtained:

$$\left(\frac{S_{opt}}{D} \right) \cong 4. \left(\frac{H}{H-D} \right)^{2/3} . Re_D^{-1/2} . Pr^{-1/5} \quad (9)$$

Maximum heat transfer rate can be obtained by substituting equation S_opt into equation (6) or equation (8).

RESULT AND DISCUSSION

In the present study, as shown in Figure 1, the diameter and length of tank for optimization procedure are 85 mm and 400 mm, respectively. The results obtained for MH tanks were presented at different equilibrium pressures varying from 60 to 120 kPa and different ambient temperatures varying from 290 to 310 K. Table 1 shows that maximum heat transfer and optimum spacing changes between ~0.09 and ~0.016 for different equilibrium pressure according to various ambient temperatures (290 K, 300 K and 310 K). As a result, by increasing Reynolds number, the optimal spacing will considerably decrease. It is noticed that, at Reynolds number of $3.0\text{x}10^4$ optimum spacing is the lowest. Furthermore, the optimal spacing is the same by decreasing the equilibrium pressure and increasing ambient temperature. Therefore, those variables cannot reduce the optimum spacing, significantly. Moreover, As the spacing (S) is bigger or less than optimum spacing, heat transfer decreases, therefore the optimum spacing improves the overall heat transfer between tanks and air stream.

Table 1. Maximum Heat Transfer and Optimum Spacing According to Reynolds Number and Equilibrium Pressure for Different Ambient Temperatures

(T_{amb}=290 K)							
P_{eq} (kPa)	T_w (K)	Re=6000		Re=12000		Re=30000	
		S_{opt} (m)	Q (W)	S_{opt} (m)	Q (W)	S_{opt} (m)	Q (W)
120	289.0	0.016	-60	0.012	-105	0.09	-209
100	284.9	0.016	-363	0.012	-631	0.09	-1255
60	274.1	0.016	-970	0.012	-1688	0.09	-3355
(T_{amb}=300 K)							
P_{eq} (kPa)	T_w (K)	Re=6000		Re=12000		Re=30000	
		S_{opt} (m)	Q (W)	S_{opt} (m)	Q (W)	S_{opt} (m)	Q (W)
120	289.0	0.016	-668	0.012	-1150	0.09	-2395
100	284.9	0.016	-970	0.012	-1680	0.09	-3441
60	274.1	0.016	-1615	0.012	-2786	0.09	-5542
(T_{amb}=310 K)							
P_{eq} (kPa)	T_w (K)	Re=6000		Re=12000		Re=30000	
		S_{opt} (m)	Q (W)	S_{opt} (m)	Q (W)	S_{opt} (m)	Q (W)
120	289.0	0.016	-1262	0.012	-2197	0.09	-4362
100	284.9	0.016	-1564	0.012	-2720	0.09	-5408
60	274.1	0.016	-2170	0.012	-3779	0.09	-7508

The results according to Reynolds number and ambient temperature are shown Figure 5 for Peq = 60, 100 and 120 kPa, respectively. It can be seen from these plots that the maximum heat transfer rate occurs at S=0.09, 0.012 and 0.016 mm. The fact that the increase in T_{amb} effects the heat transfer rate an increase. It appears that the heat transfer rate increases monotonically with Reynolds number for all values. Figures show the existence of a local optimal spacing. As an example according to Figure 5 at Reynolds number of 3.0x10^4, maximum heat transfer gain, in comparison with the arbitrary arrangement, was observed for optimal arrangement with S=0.09. From numerical results obtained in this study, it is important to stress that a heat transfer gain of up to 13 % was observed in the optimum arrangement with S=0.09, 0.012 and 0.016 m.

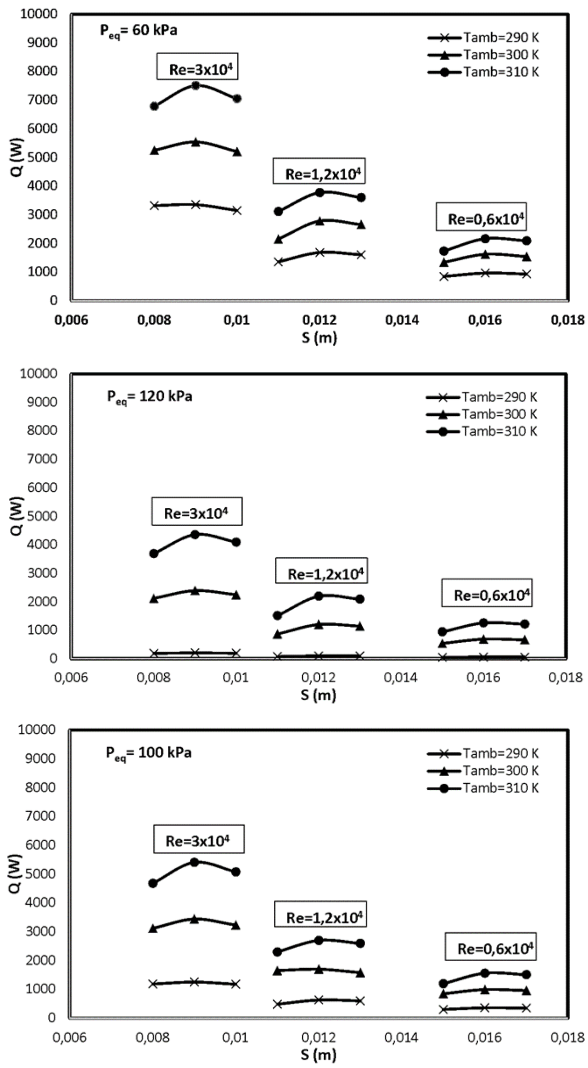

Figure 5. Variation of the Heat Transfer According to Re Number and Ambient Temperature for Peq

CONCLUSIONS

Metal hydride hydrogen storage systems are generally characterized by reaction kinetics of hydrogen absorption and desorption. Most important parameter of metal hydride is reaction enthalpy. This is strongly related to thermal management. Therefore, thermal management of these systems during reactions is a challenge.

This study reports fundamental results for the selection of the spacing between horizontal tanks in an array of defined volume in forced convection conditions. The optimal spacing formulated in equation (9) corresponds to the maximum heat transfer between the entire metal hydride tanks and surrounding fluid.

This study also presents that there exists a distance between the MH tanks for which the Heat transfer is maximum. Results show that the usage of optimum spacing can be a useful way to enhance the hydrogen flow rates of both absorption and desorption. By increasing the Reynolds number, the optimal spacing was reduced more than half. Moreover, the equilibrium pressure and ambient temperature were not affected with optimum spacing. The present results indicate the need of optimization and motivate the development of a general numerical model such that optimal arrangements of MH tanks could be searched according to different parameters simultaneously for maximum heat transfer. Such globally optimized configurations are expected to be of great importance for MH banks design and for the generation of optimal flow structures in general.

This simple model also offers the advantage of ease in manufacturing. However, a good heat exchanger design is not sufficient to enhance the hydrogen flow rates of both absorption and desorption. The model could be very effective for designing of metal hydride tank banks with higher Hydrogen capacity and faster kinetics. The optimization approach accounts for the other geometrical configuration. It is simple enough to apply to integrated hydride tank – fuel cell systems in order to develop control systems and strategies..

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