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OPTIMUM SPACING BETWEEN HORIZONTAL METAL HYDRIDE (MH) HYDROGEN STORAGE TANKS INTEGRATED WITH FUEL CELL POWER SYSTEM IN NATURAL CONVECTION

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Abstract: Present investigation examines the ability of metal hydride storage systems to supply hydrogen to a fuel cell, when the metal hydride tanks are heated by natural convection. To determine optimum spacing of horizontal MH tanks in desorption process, theoretical and numerical analysis is presented to compare different storage tank configurations. Three configurations are analyzed: storage cases with H/D=3, 5 and 10 (array height H, cylinder diameter D). Each of the three configuration had different number of cylinders in the array depending on the H/D and spacing between the cylinders. As MH alloys, AB_5 type alloy ($LaNi_5$) is selected. The analysis takes into account the effect of external natural convection heat transfer and reaction kinetics of MH. The spacing is calculated by maximizing the heat transfer by means of accurate correlations. The results of this study reveal that there exists a distance between the MH tanks for which the Nusselt number is maximum. By increasing H/D or decreasing the Rayleigh number, the optimal spacing will increase. Moreover by increasing Rayleigh numbers optimum spacing will increase more than 20%. These results show the optimum spacing in a given volume increase with the increasing equilibrium pressure and H/D ratio.

Keywords: Hydrogen Storage, Metal Hydrides, Natural Convection, Computational fluid dynamics.

DOĞAL TAŞINIM ORTAMINDA YAKIT PİLİ GÜÇ SİSTEMİ İLE ENTEGRE YATAY METAL HİDRİD (MH) TANKLAR ARASINDAKİ OPTİMUM ARALIK

Özet: Mevcut araştırma doğal taşınımla ısıtılan metal hidrid tankların yakıt piline sağlaması gereken Hidrojen kapasitesini incelemektedir. Deşarj işleminde, tanklar arasındaki optimum aralığı tespit etmek için, farklı konfigürasyonlarda teorik ve sayısal analizler yapılmıştır. H/D=3, 5 ve 10 için analizler yapılmıştır. Bu üç konfigürasyon, H/D ve aralığa bağlı olarak, farklı sayıda tanktan meydana gelmektedir. Metal hidrid olarak AB_5 tipi $LaNi_5$ seçilmiştir. Analizlerde doğal taşınım ve MH' in reaksiyon kinetikleri hesaba katılmıştır. Aralık, maksimum ısı transferini sağlayacak şekilde uygun bağıntılarla hesaplanmıştır. Sonuçlar, maksimum Nusselt değeri için tanklar arasında optimum bir aralık olduğunu göstermiştir. H/D' nin artması veya Rayleigh sayısının azalması ile optimum aralık değeri artmaktadır. Ayrıca, Rayleigh sayısının artması ile optimum aralık %20' den fazla artmaktadır. Bu sonuçlar göstermiştir ki, optimum aralık denge MH denge basıncının ve H/D' nin artması ile artacaktır.

Anahtar Kelimeler: Hidrojen Depolama, Metal Hidrid, Doğal Taşınım, Hesaplamalı Akışkanlar Dinamiği.

NOMENCLATURE

H	Array height [mm]
D	Diameter [mm]
L	Length [mm]
W	Width [mm]
Q	Heat transfer [W]
P_{eq}	Equilibrium Pressure [kPa]
S	Spacing [mm]
T	Temperature [K]

INTRODUCTION

Economic and environmental considerations have brought the need for performance improvement on all engineering applications, aiming to rationalize the use of available energy and reduction of lost work. Many industrial applications have to size according to space availability. The optimization problem consists on the finding the optimal spacing between cylinders of a known geometry, such that maximum heat transfer between the cylinders and surrounding fluid is achieved. Generally, such the optimization technique is on the development of cooling for electronic packages (Matos et al., 2001). The numerical solution of the laminar free convection of air around a horizontal cylinder with external longitudinal fins was studied by Dogan et al., 2012, who investigated the effects of geometric parameters fin diameter, fin spacing and base-to-ambient temperature difference on the heat transfer performance of fin arrays. Hydrogen storage has been subject of intensive research of many years. There are currently three main technologies for storing hydrogen: as a compressed gas, as a liquefied cryogenic fluid, and as a solid in a metal hydride (Jiang et al., 2005). Metal hydrides are inherently safer than compressed gas or liquid hydrogen and have a higher volumetric hydrogen storage capacity. Metal hydrides begin as intermetallic compounds produced in much the same way as any other metal alloy. When they are exposed to hydrogen at certain pressures and temperatures, they absorb large amounts of the gas and form metal hydride compounds and hydrogen placed compactly into metal lattice. The hydrogen consumption varies according to the energy demand of the user. Therefore a hydrogen tank is needed to store the hydrogen excess produced during low consumption periods and to deliver it during high consumptions periods. To decrease the hydrogen discharging time, the heat transfer capability has to be improved. Researches with metal hydrides are related to the development of the metal hydride storage capacity, detailed analyses of heat and mass transfer inside a tank for hydrogen absorption and desorption processes and performance analyses of hydrogen discharge process between single metal hydride tank and fuel cell system (McDonald et al., 2006; McDonald et al., 2006; McDonald et al., 2007; Muthukumar et al. 2009; Forde et al. 2009; Guizzi et al. 2009; Phate et al. 2007; Chung et al. 2009. Mellouli et al. 2010; Raju et al. 2012; Melnichuk et al. 2009; Ye et al. 2010). Increasing heat transfer rates in MH tanks is important for optimizing the design of hydrogen storage applications (Hilali et al. 2012). Although there are several theoretical and experimental studies in the literature on the various aspects of the hydrogen storage processes. There are no studies investigating various arrangements of tank banks on dehydriding process. The optimal spacing is important particularly because of its obvious implications on the design of arrangements of hydrogen tank banks for fuel cell applications.

A detailed and systematic analysis on the effects of arrangements of tank banks on the performance and hydrogen absorption/desorption processes is needed to optimize the metal hydride hydrogen storage systems. Therefore, in this study, a mathematical model is developed to comprehensively investigate the effects of arrangements of tank banks of spacing for horizontal MH tanks on the hydrogen desorption processes, and numerical simulations are conducted for the hydrogen discharging processes in cylindrical AB_5 metal hydride tanks under various spacing between tanks. In the following sections, a detailed description of the mathematical model is given first, followed by the results and discussion and the conclusion.

MATHEMATICAL FORMULATION

As seen in Figure 1, we assume that horizontal bundle of cylinders are staggered and that their centers form equilateral triangles. Three configurations are analyzed: storage cases with H/D=3, 5 and 10. Each of the three configuration had different number of cylinders in the array depending on the H/D and spacing between the cylinders. The used metal hydride tanks exchanges heat through lateral and base areas. Cylinders are cooled by natural convection in the space of height H, length L and width W. The tanks contain the MH alloy $LaNi_5$. Natural convection heat transfer (q) occurs between the cylinder surfaces (T_w) and the surrounding fluid reservoir (T_∞).

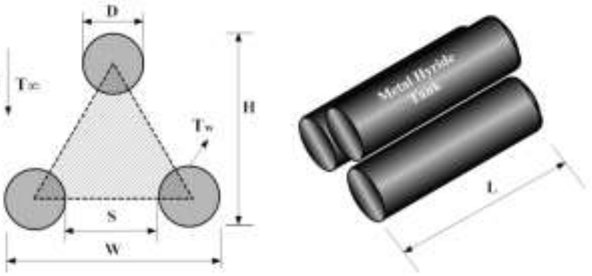


Figure 1. Configuration of the horizontal metal hydride tanks

In this study, Autodesk Simulation CFD package was used to illustrate the results of storage cases with H/D=3, 5 and 10. In the analysis, steady state solutions are obtained by using the zero-equation-turbulence model with initial ambient air temperature of 20 ^{o}C. Air is taken as an ideal gas at atmospheric pressure. All tanks are subjected to boundary conditions with ambient pressure P and ambient temperature $T\infty$ and tank surface temperature T_w. Figure 2 shows the geometry of the computational domain of the metal hydride tanks. This geometry is used to illustrate the methodology for developing expressions for the optimal dimensions of tank banks using CFD. In the design, H and W are the design variables for the tank array considered in this study.

The assumptions and equations governing heat transfer used in this study are described in the following.

1. The flow is steady.
2. Cylinder surface temperature is uniform.
3. Heat gain through the ends of cylinder is negligible.
4. Contact resistance between tank wall and metal hydride is negligible.
5. W=H

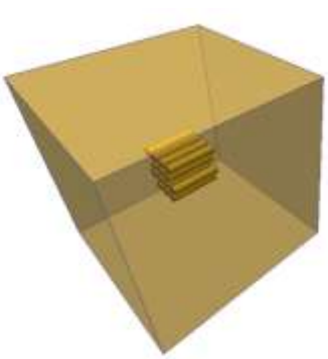


Figure.2. The geometry of the computational domain of the metal hydride tanks

The equilibrium pressure of desorption is calculated using the van't Hoff relationship. The relationship of various representative AB_5 alloys are shown in Figure 3 (Sandrock, 1999).

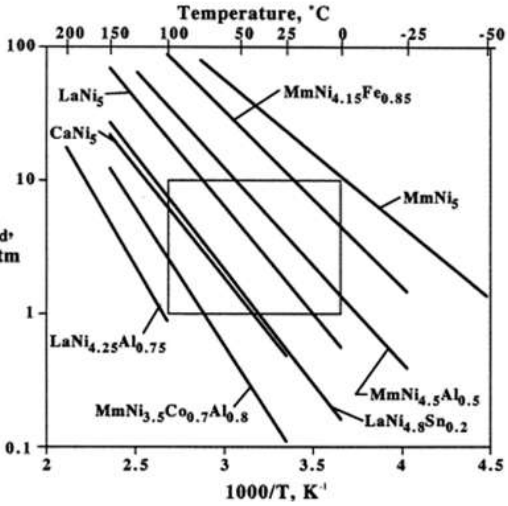


Figure 3. Van't Hoff plots for various AB_5 hydrides

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

$$ln\, P_{eq} = A - \frac{B}{T} \tag{1}$$

where A and B for P_{eqa} are determined from the Hydride Material Listing Database as A = 17.608 and B =3704.60, and A and B for P_{eqd} are determined as A = 17.478 and B =3704.60 (McDonald, 2006).

The formulation consists of two steps (Bejan et al., 1995). In the first step, we identify to extremes:

For large spacing, the heat transfer from one cylinder is

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

Where Nusselt number is determined using the correlation due to Churcill and Chu: [18]:

$$Nu_D = \left\{0{,}60 + \frac{0{,}387\, Ra_D^{1/6}}{\left[1+(0{,}559/Pr)^{9/16}\right]^{8/27}}\right\}^2 \quad Ra_D \le 10^{12} \tag{3}$$

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

$$Ra_D = \frac{g\beta D^3\,(T_w - T_\infty)}{\alpha\, \upsilon}$$

Where g is the acceleration due to gravity, T_w is the temperature on the surface on the tank, β is the volumetric thermal expansion coefficient which is obtained depends on the film temperature ($T_f = (T_w - T_\infty)/2$), υ is the kinematic viscosity, and α is the thermal diffusivity.

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

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

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

$$q_{large} = q_1 * n \tag{5}$$

$$q_{large} \cong 20{,}36 \frac{HLW}{(S+D)^2}\, k(T_w - T_\infty) \left\{0{,}60 + \right.$$

0,387 RaD161+(0,559Pr)9168272

(6)

For small spacing, we are assuming cylinders 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):

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

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:

$$q_{small} = \frac{\left(\frac{S(S+2D}{S+D}\right)^3 LW}{12\, D^3\, (S+D)} k(T_w - T_\infty)\, Ra_D \tag{8}$$

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 4, 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 (Bejan, 1984) and by Sadeghipour and Pedram Razi (Sadeghipour and Razi, 2001). The following optimum spacing formula is obtained.

$$\frac{S_{opt}}{D}\left(\frac{S_{opt}/D+2}{(S_{opt}/D+1)^{2/3}}\right) = 6{,}25\, \left(\frac{H}{D}\right)^{1/3} \left\{0{,}60 + \right.$$

0,387 RaD161+(0,559Pr)91682723RaD−13

(9)

Maximum heat transfer rate can be obtained by substituting equation S_{opt} into equation (6) or equation (8).

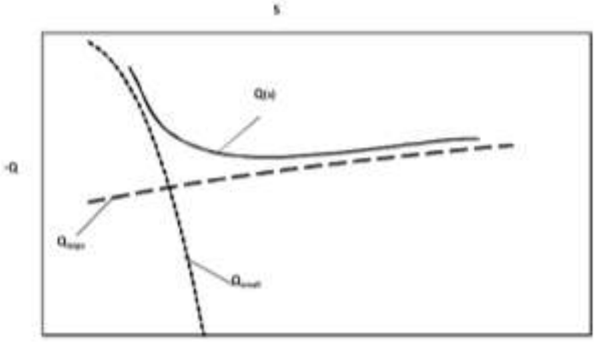


Figure 4. The optimum spacing as the intersection of the Q_{large} and Q_{small} asymptotes

RESULTS AND DISCUSSION

In this section, the main results of the present work are presented and discussed according to the optimization objectives and the variables. The results are summarized in tables in such a way that useful information is easily extracted, together with the equations for predicting the optimum tanks arrangement design deduced in the previous section. The numerical results were obtained using the equations described in Section 2.

According to Figure 1, the dimensions of optimization procedure were L=500 mm and D=100 mm. Maximum heat transfer and optimum spacing for different equilibrium pressure are shown in tables 1, 2 and 3. Table 1 shows that optimum spacing changes between ~0.015 and ~0.045 for different equilibrium pressure according to H/D=3. Table 2 shows that optimum spacing changes between ~0.019 and ~0.053 for different equilibrium pressure according to H/D=5. Table 3 shows that optimum spacing changes between ~0.024 and ~0.067 for different equilibrium pressure according to H/D=10.

Table 1. Maximum heat transfer and Optimum Spacing for different equilibrium pressure (H/D=3)

P_{eq} (kPa)	T_w (K)	S_{opt} (m)	$Ra_D x10^5$ (-)	Q (W)
160	295.6	0.04435	0.043	-1.459
140	292.5	0.02526	0.376	-24.56
120	289.0	0.02111	0.764	-60.8
100	284.9	0.01874	1.230	-110.4
80	280.1	0.01703	1.800	-177.2
70	277.3	0.0163	2.140	-219.5
60	274.1	0.01563	2.550	-269.8

Table 2. Maximum heat transfer and Optimum Spacing for different equilibrium pressure (H/D=5)

P_{eq} (kPa)	T_w (K)	S_{opt} (m)	$Ra_D x10^5$ (-)	Q (W)
160	295.6	0.053	0.043	-2.139
140	292.5	0.030	0.376	-36.45
120	289.0	0.025	0.764	-90.48
100	284.9	0.022	1.230	-164.6
80	280.1	0.020	1.800	-264.6
70	277.3	0.019	2.140	-327.8
60	274.1	0.0186	2.550	-403.2

Table 3. Maximum heat transfer and Optimum Spacing for different equilibrium pressure (H/D=10)

P_{eq} (KPa)	T_w (K)	S_{opt} (m)	$Ra_D x10^5$ (-)	Q (W)
160	295.6	0.06681	0.043	-3.918
140	292.5	0.0381	0.376	-68.65
120	289.0	0.03182	0.764	-171.8
100	284.9	0.02824	1.230	-313.9
80	280.1	0.02566	1.800	-506.4
70	277.3	0.02456	2.140	-628.5
60	274.1	0.02353	2.550	-774.1

As a result, Q and S vary significantly with equilibrium pressure. The significant point is that decreasing the equilibrium pressure will decrease the optimal spacing of metal hydride tanks. For given H/D, heat transfer was computed with Equations 6 and 8, for the range $0<S\leq0.06$. The same procedure was repeated for H/D=3, 5 and 10. The results according to tank-to-tank spacing and various values of H/D are shown Figure 5 and 6, for different Ra_D. The results indicate optimum points for all H/D and S. The influence of the variation of Ra_D is also investigated. As Ra_D increases Q increases. The heat transfer is less for lower values of Ra_D. Figure 5 shows that for H/D=3, 5 and 10 and, Q_{max} according to S_{opt} is smaller for Ra_D =1.22x105 than for 1.81x105. Figures 5-6 show the effect of Ra_D number and H/D: optimum spacing which corresponds to maximum heat transfer, decreases with increasing Ra_D at various values of H/D, where the tanks were almost touching each other.

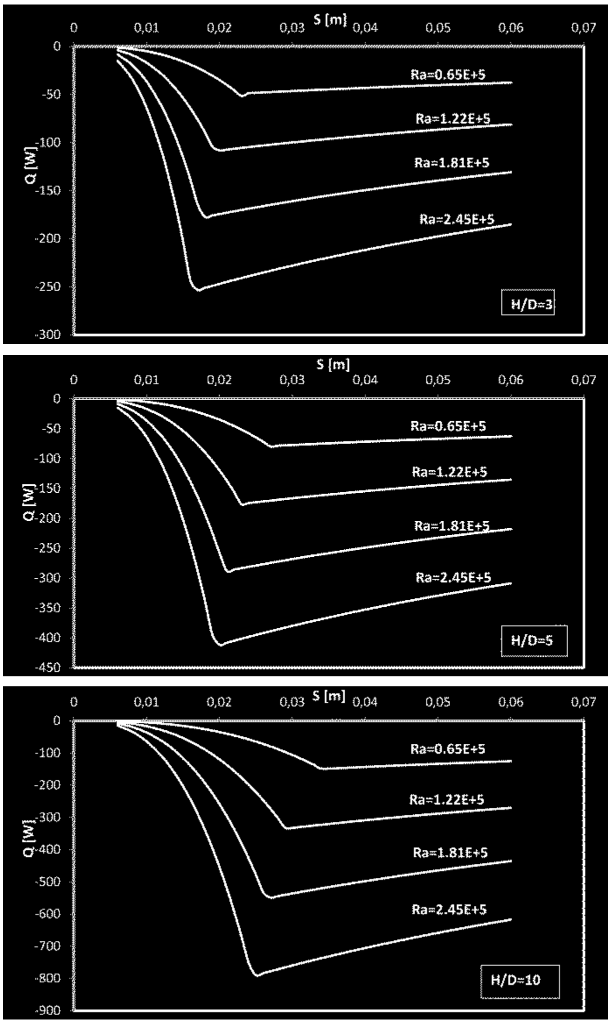


Figure 5. Variation of the heat transfer with the spacing for different Ra_D

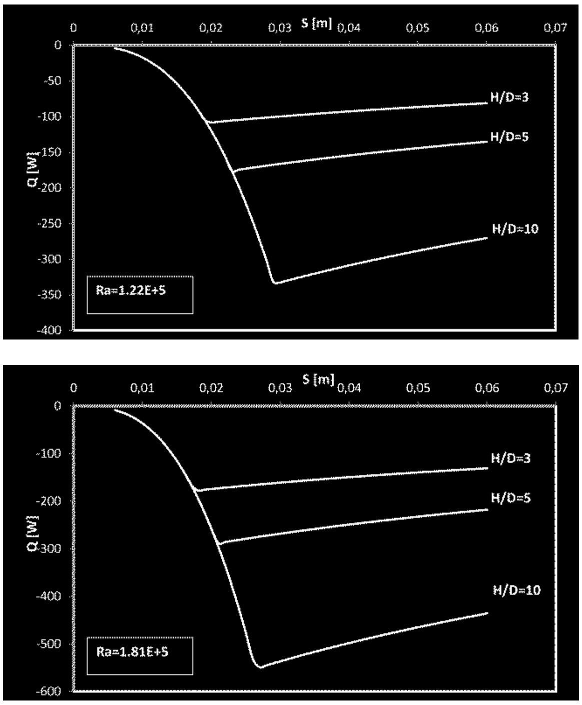
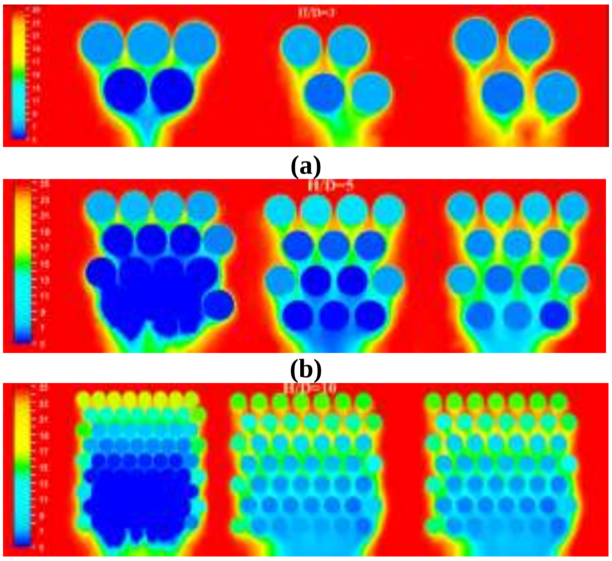


Figure 6. Variation of the heat transfer with the spacing for different H/D

These results show the optimum spacing in a given volume increase with the increasing equilibrium pressure and H/D ratio. Several checks were performed in order to verify the generated results. The contour plots for velocity and temperature were observed separately to ensure that the results satisfy the boundary conditions. Figure 7 and 8 provides profiles indicating the distributions of temperature and velocity on the surface of the horizontal cylinder arrays for three different H/D when S equals to 10, 20 and 30, respectively. Scales are in ^{o}C for temperature and mm/s for velocity contours, respectively.

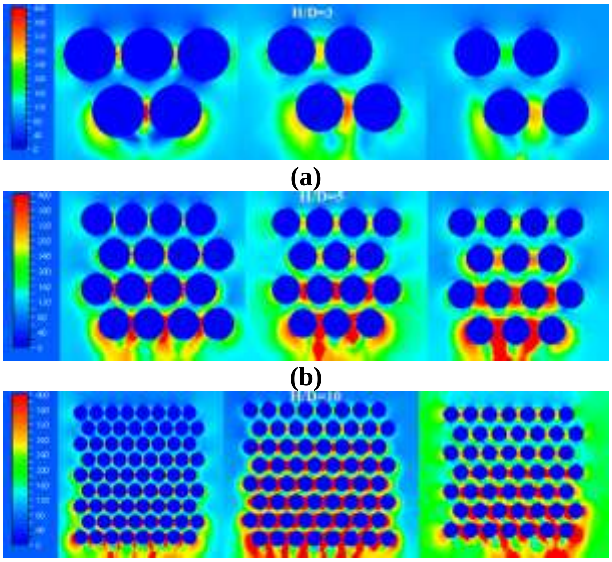


(a)

(b)

(c)

Figure 7. The profile of temperature on the surface of the horizontal cylinder arrays. (a) S= 10, 20 and 30 for H/D=3 (b) S= 10, 20 and 30 for H/D=5 (c) S= 10, 20 and 30 for H/D=10



(a)

(b)

(c)

Figure 8. The profile of velocity on the surface of the horizontal cylinder arrays. (a) S= 10, 20 and 30 for H/D=3 (b) S= 10, 20 and 30 for H/D=5 (c) S= 10, 20 and 30 for H/D=10

It is evident that the spacing and aspect ratio (H/D) are affecting this temperature and flow distribution. Comparing the three temperature profiles, we can see that the temperature distribution in the vicinity of the inlet region is almost identical for all cases. As we see, the temperature profiles around the tanks surface are different for S=10, 20 and 30 cases. The air temperature decreases along array and its distribution is approximately symmetrical with respect to front-plane. We observe a gradual increase in optimum spacing from the value of 10 to the value of about 30 corresponding to the H/D with natural convection. For optimum spacing the best value founded was about between 15 and 25 for H/D 3,5,10 and the equilibrium pressure value of 70 kPa. The air temperature is lower along the channel in the vicinity of the inner tanks, also because of the increased air flow acceleration along those regions which it appears more apparent with aspect ratio (H/D), as can be seen in figure 8. Thus, the temperature between the tanks surface for the optimum spacing is distinctly lower than that in the corresponding region for the other spacings. The significant point is that increasing the number of cylinders or the cylinder to cylinder spacing or decreasing the Ra_D will increase the optimal spacing. This leads to extra enhancement of the heat transfer from the tanks arrays at high Ra_D.

CONCLUSION

In this study we developed fundamental results for the selection of the spacing between horizontal tanks in an array of defined volume. The heat transfer is by laminar natural convection. The optimal spacing formulated in equation (9) corresponds to the maximum heat transfer between the entire metal hydride tanks and surrounding fluid.

The results of this study reveal that there exists a distance between the MH tanks for which the Nusselt number is maximum. By increasing H/D or decreasing the Ra_D, the optimal spacing will increase. Moreover by increasing Rayleigh numbers optimum spacing will increase more than 20%. Flow around tanks in the first row bank corresponds to that for a single cylinder in cross flow. For other rows, flow depends strongly on the tank arrangement and aspect ratio (H/D). If it is intended to achieve this increase, it can be realized by increasing the equilibrium pressure. However, this would not be a favorable design option because of the study characteristics of MH. Therefore 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.

The current study can assist in tank design for a particular application leading to improvements in performance. 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.

REFERENCES

Bejan A., 1984, *Convection Heat Transfer*, Wiley, New York.

Bejan A., Fowler A. J., Stanescu G.J., 1995, the Optimal Spacing between Horizontal Cylinders in a Fixed Volume Cooled By Natural Convection, Int. *J. Heat and Mass Trans*., 38, 2047- 55.

Chung C.A. and Ho C. J., 2009, Thermal–Fluid Behavior Of The Hydriding And Dehydriding Processes in a Metal Hydride Hydrogen Storage Canister, *Int. J. Hydrogen Energy*, 34, 4351–64.

Dogan A., Akkus S. and Baskaya S., 2012, Numerical Analysis Of Natural Convection Heat Transfer From Annular Fins on a Horizontal Cylinder, *J. Thermal Science and Technology*, 32, 31-41.

Førde T., Eriksen J., Pettersen AG. and Vie PJS., 2009, Thermal Integration of a Metal Hydride Storage Unit and a PEM Fuel Cell Stack, *Int. J. Hydrogen Energy*, 34, 6730-9.

Guizzi GL., Manno M. and De Falco M., 2009, Hybrid Fuel Cell-Based Energy System with Metal Hydride Hydrogen Storage for Small Mobile Applications, *Int. J. Hydrogen Energy*, 34, 3112-24.

Hilali I., 2012, On the Optimum Sizing of Metal Hydride Tank Filled AB_2 Type Alloy, *J. Renewable and Sustainable Energy*, 4, 033121.

Incropera Frank P., 2007, *Fund. of Heat and Mass Transfer* (Sixth ed.), Wiley, New York.

Jiang Z. R. A. and Dougal A. D., 2005, Simulation of Thermally Coupled Metal Hydride Hydrogen Storage and Fuel Cell Systems, *J. Power Sources*, 142, 92–102.

MacDonald BD. and Andrew M. R., 2006, Impacts of External Heat Transfer Enhancements on Metal Hydride Storage Tanks, *Int. J. Hydrogen Energy*, 31, 1721 – 31.

MacDonald BD. and Andrew M. R., 2007, Experimental and Numerical Analysis of Dynamic Metal Hydride Hydrogen Storage Systems, *Int. J. Power Sources*, 17, 282–293.

MacDonald BD. and Andrew M. R., 2006, Thermally Coupled Metal Hydride Hydrogen Storage and Fuel Cell System, *J. Power Sources*, 161, 346-55.

Matos R. S., Vargas J. V. C., Laursen T. A. and Saboya F. E. M., 2001, Optimization Study and Heat Transfer Comparison of Staggered Circular and Elliptic Tubes in Forced Convection, *Int. J. Heat and Mass Transfer*, 20, 3953-3961.

Mellouli S., Askri H. and Dhaou A., 2010, Numerical Simulation of Heat and Mass Transfer in Metal Hydride Hydrogen Storage Tanks for Fuel Cell Vehicles, *Int. J. Hydrogen Energy*, 35, 1693–1705.

Melnichuk M., Silin N. and Peretti H.A., 2009, Optimized Heat Transfer Fin Design for a Metal-Hydride Hydrogen Storage Container, *Int. J. Hydrogen Energy*, 34, 3417–24.

Muthukumar P. and Venkata R. S., 2009, Numerical Simulation of Coupled Heat and Mass Transfer in Metal Hydride-Based Hydrogen Storage Reactor, *J. Alloys and Compounds*, 472, 466–472.

Phate A. K. and Maiya S. S., 2007, Simulation of Transient Heat and Mass Transfer during Hydrogen Sorption in Cylindrical Metal Hydride Beds, *Int. J. Hydrogen Energy*, 32, 1969–81.

Raju M. and Kumar S., 2012, Optimization of Heat Exchanger Designs in Metal Hydride Based Hydrogen Storage Systems, *Int. J. Hydrogen Energy*, 37, 2767–2778.

Sadeghipour M. S. and Pedram R., 2001, Natural Convection from a Confined Horizontal Cylinder: the Optimum Distance between the Confining Walls, *J. Heat and Mass Trans*fer, 44, 367-74.

Sandrock G., 1999, A Panoramic Overview of Hydrogen Storage Alloys From a Gas Reaction Point of View, *J. Alloys and Compounds*, 29, 877–888.

Ye J., Jiang L., Li Z., Liu X. and Wang S., 2010, Numerical Analysis of Heat and Mass Transfer during Absorption of Hydrogen in Metal Hydride Based Hydrogen Storage Tanks, *Int. J. Hydrogen Energy*, 35, 8216–24.