INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 43 (2018) 17970–17977

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

A study on ideal distance between staggered metal hydride tanks in forced convection

İsmail Hilali [a,*], Refet Karadag [b], Hüsamettin Bulut [a], M. Azmi Aktacir [a]

[a] Mechanical Engineering Department, Harran University, Sanliurfa, 63000, Turkey

[b] Mechanical Engineering Department, Adıyaman University, Adıyaman, 02100, Turkey

ARTICLE INFO

Article history:
Received 23 November 2017
Received in revised form
7 March 2018
Accepted 8 March 2018
Available online 2 April 2018

Keywords:
Metal hydride storage
Optimization
Forced convection
Numerical analysis

ABSTRACT

There are several critical parameters in specifying the satisfactory hydrogen flow in metal hydride tanks such dynamic factors in addition to the quantity contained in the tanks. Dynamic factors could be emphasized as ambient conditions and metal hydride properties. This work aims at investigating the effects of equilibrium pressure, ambient air temperature and velocity on ideal distance among metal hydride (MH) tanks used with the purpose of storing hydrogen in fuel cell applications as theoretically and numerically by using Autodesk CFD Simulation software. The metal hydride chosen for the present study is titled as $LaNi_5$ in the literature. A new approach was utilized in the present study to describe the ideal distance among MH tanks using a novel approach in operating different conditions. Analyses implemented in this study are based on various ambient temperatures (i.e. 290K, 300K & 310K), Reynolds Numbers (i.e. 6000, 12,000 & 30,000) and equilibrium pressures (i.e. 60 kPa, 100 kPa & 120 kPa). As emphasized here, the ideal distance among MH tanks will be rather shortened while the Reynolds numbers increase during the operation. Moreover, it is noted here that the ideal distance will not be changed while the equilibrium pressure is in decrease and the ambient temperature is on the increase. Our findings indicate that distance among the MH tanks exists for maximum heat transfer. This finding could be utilized to maximize efficiency of the integrated metal-hydride-Fuel cell system without increasing additional costs.

Introduction

The diversity of availability and the renewability of hydrogen have opened the way for use in different engineering applications with the creation of an environmentally friendly [1]. The benefits of fuel cells should be reflected in hydrogen storage systems to ensure it works efficient way. Several techniques are utilized in the systems of hydrogen storage namely metal hydride, compression and liquefaction. The Hydrogen storage as a metal hydride is popular than other Hydrogen storage methods. The advantages of the above-mentioned techniques could be counted as reliability, safety and the capacity of hydrogen storage. The process of charging and discharging hydrogen within metal hydride cause two types of critical reactions namely exothermic and endothermic ones. These processes also require the control and enhancement of appearing thermal energy and efficiency. The

* *Corresponding author.*
E-mail addresses: ihilali@gmail.com (İ. Hilali), refetkaradag@yahoo.com (R. Karadag), hbulut@harran.edu.tr (H. Bulut), maktacir@gmail.com (M.A. Aktacir).
https://doi.org/10.1016/j.ijhydene.2018.03.051
0360-3199/

effective utilization of hydrogen in metal hydride tanks could be realized in controlling thermal energy. It is therefore important to provide adequate hydrogen from tank to the system of a fuel cell with the purpose of enhancing the capability of the heat transfer. Inefficient thermal energy is considered as one of the most important disadvantages in the metal hydride and deal with the arrangement of metal hydride tanks due to the emphasis on the literature. Several models considering the power of mathematics have been developed to bring a proper solution in analyzing the properties of metal hydride tanks related to heat transfer. Afzal et al. [2] reviewed the existing literature a classification of heat transfer techniques and their relative effectiveness assessed with respect to system scale. They were observed that improvement of only thermal conductivity or heat transfer coefficient will not be able to improve system performance. An effective design should take into account the influence of both these parameters concurrently. Brikia et al. [3] were evaluated the experimental studies of the hydrogen absorption phenomenon in different reactors based on metal hydrides. The characteristics of the reaction kinetics in three different reactors using the same measurement conditions were compared. A numerical model describing the reaction kinetics of the H_2 absorption by $LaNi_5$ alloy validates the results were obtained. Of these results, it is found that the rate constant varies from one reactor to another. Mohammadshahi et al. [4] analyzed the mathematical models developed in previous studies that indicate a characteristic of variously applied equations, different assumptions and solution techniques. The performance of metal hydride concerning their effective factor, cooling system configurations and advanced reactor geometries are also evaluated by Mohammadshahi et al. Chibani and Bougriou [5] presented a numerical study of solid-state hydrogen storage and destocking in the Lanthanum Nickel ($LaNi_5H_2$) in a concentric triple-tube heat exchanger. Moreover, the influence of the thermal-reactor geometry for the storage and destocking hydrogen have been examined by changing the diameters of the heat exchanger. Andrea Mazzuccoa and Martin Dornheimb [6] examined advanced techniques relevant to the effective use of heat management systems integrated to metal hydride storage tanks. Moreover, they presented limitations and performance enhancements of developed solutions for heat management systems. Studies predicated upon alternative geometrical solutions and/or operation techniques are considered, what's more, their related preferences are clarified. . Improving heat transfer during hydrogen take-up and release has observed to be fundamental to enhance storage limits and limit time necessities. Shahin Shafieea and Mary Helen McCay [7] focus on the issue of thermal control while concentrating on reactor and heat exchanger setups. In the study, alternative reactors and heat exchangers for metal hydride storage systems are investigated, classified and compared. Bhogilla [8] designed metal hydride tank for stationary application and developed 3D numerical model. Veerraju and RamGopa [9] presented time-dependent heat and mass transfer model to anticipate the usability of elliptical tube metal hydride reactors and obtained ideal solutions for the elliptical hydride tube bank reactors. Bhouria and Goyette [10] investigated numerically the enhancement of the hydrogen by maximizing the heat transfer rate charging in a multi-tubular metal hydride reactor with longitudinal fins. optimized the design parameters on the hydrogen charge capacity is defined. Johnson et al. [11] designed, fabricated, and tested a prototype metal hydride tank which was optimized by maximizing the effectiveness of heat transfer properties. Raju and Kumar [12] investigated optimization of heat exchanger design with computational fluid dynamics and different types of heat exchanger designs have been examined in terms of geometric parameters. MacDonald and Rowe [13] have analyzed models to increase heat the effects of external convection resistance on thermal behavior in a tank. Jemni and Nasrallah [14] proposed an analytical model for time-dependent heat and mass transfer in the metal-hydride tank. Aldas et al. [15] analyzed thermal behavior in the metal hydride reactor. Bao et al. [16,17] and Cho et al. [18] modelled metal hydride storage mechanism according to the design parameters and various operating conditions. Minko et al. [19,20] studied heat and mass transfer in metal hydride as a porous medium. Ma et al. [21] derived heat transfer equations of metal hydride tank according to different fin properties. Nakano et al. [22] designed and fabricated a novel metal-hydride tank with coiled heat exchanger. Dhaou et al. [23] studied and compared different metal hydride tank with spiral heat exchangers according to heat transfer efficiencies Sekhar et al. [24] modelled heat-and-mass transfer in four different metal-hydride tanks for the comparison of hydrogen charging.many studies are also studied on integrated fuel cell-metal hydride system. Macdonald and Rowe [25] and Førde et al. [26] investigated thermal characteristic of integrated system. Rizzi et al. [27] constructed power system driven by the fuel cell and six metal hydride tanks and tested in different working conditions. A mathematical model was proposed for thermal management of an integrated system by Tetuko et al. [28]. Jiang et al. [29] investigated the dynamic thermal behavior of integrated metal-hydride and fuel cell system according to validated models as experimental Hilali [30] emphasized that the sequence of the tank was effective on hydrogen discharge capacity according to different thermal conditions and suggested to optimize according to hydrogen flow rate. To find an ideal arrangement, there are some correlations which they give an ideal distance for maximum heat transfer and ideal volume, in the literature [31].

Finally, this study aims to contribute to literature aspects of arrangements model of metal-hydride tank banks in different ambition conditions. Also, numerical simulations are performed in Autodesk CFD Simulation for of this model. In below sections, step-by-step formulation of the mathematical model and results were presented.

Mathematical modeling

Fig. 1 shows the schematics of the arrangement of metal hydride tanks considered in this work. $LaNi_5$ (AB_5) was selected as metal-hydride alloy because it meets low desorption pressure (~4 bar) at ambient temperature. Moreover, Reaction kinetics and thermophysical properties of $LaNi_5$ are easily found in relevant studies. For the modeling, firstly, the relevant

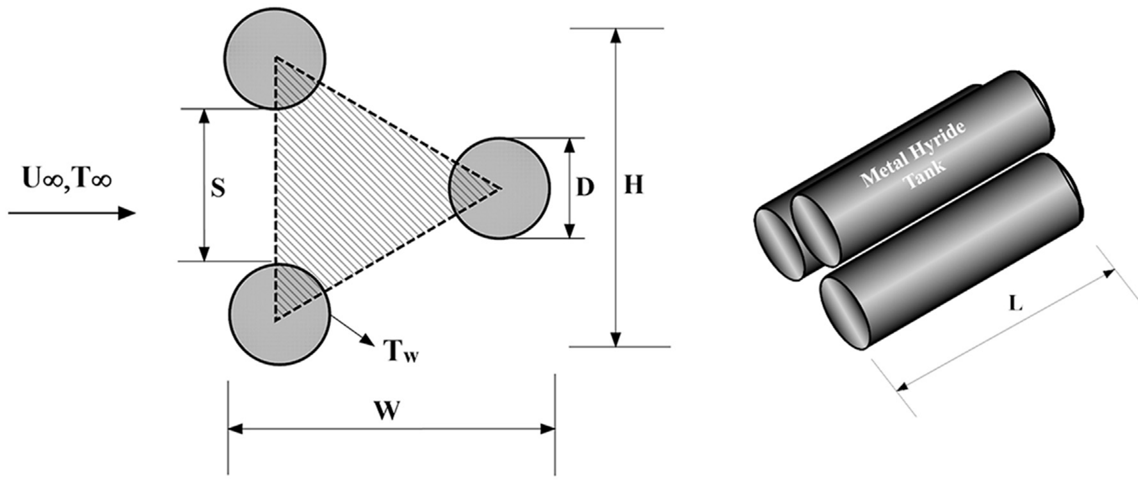

Fig. 1 – Schematic of the metal hydride tanks.

formulas and an alternative approaching are defined to obtain the ideal distance between tanks according to various internal and external conditions. Equilibrium pressures (60, 100 and 120 kPa) as internal conditions and ambient temperatures (290, 300 and 310 K), and Reynolds Numbers (6000, 12,000 and 30,000) as external conditions were assumed. These assumptions have been selected arbitrarily to study the effects of heat transfer on discharging of hydrogen. In the second step, the above scenarios were implemented to illustrate the results in Autodesk Simulation CFD package. The computational domain of bank of tanks is shown in Fig. 2. Fundamental characteristics of AB_5 alloys are shown in Fig. 3 which it is known as Van't Hoff plots [32]. The plots show the relationship between the equilibrium pressure and temperature and verify that the equilibrium pressure of the hydride bed increases with temperature. Hydrogen desorption capacity depends on temperature. To continue desorption process, metal hydride tank equilibrium pressure has to be higher than the working pressure of the fuel cell. For this reason, the metal-hydride temperature must be controlled and maintained the tank pressure above working pressure of the fuel cell that is assumed 50 kPa. For the $LaNi_5$, the equilibrium pressure is formulated according to Van't Hoff plots and calculated as:

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

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

where A and B are constant which they depend on the metal hydride type. The constants used for the present calculations are set forth [1]: A = 17.478 and B = 3704.60.

The first step

Fig. 4 shows that the possibility of the crossing point of asymptotes was used to demonstrate the presence of an ideal

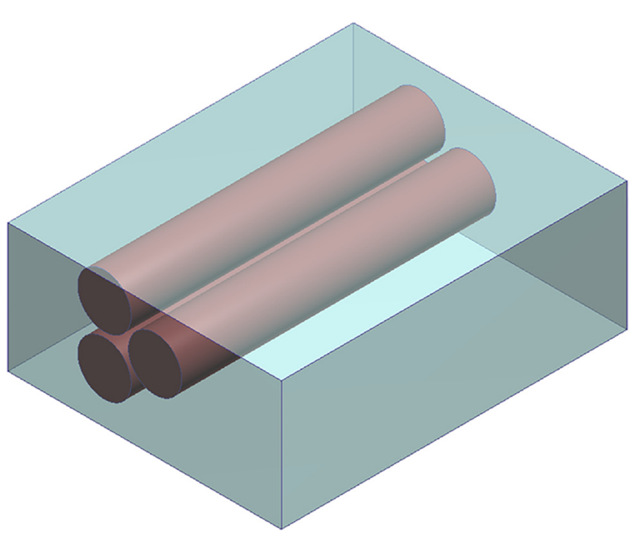

Fig. 2 – The geometry of the computational domain of the metal hydride tanks.

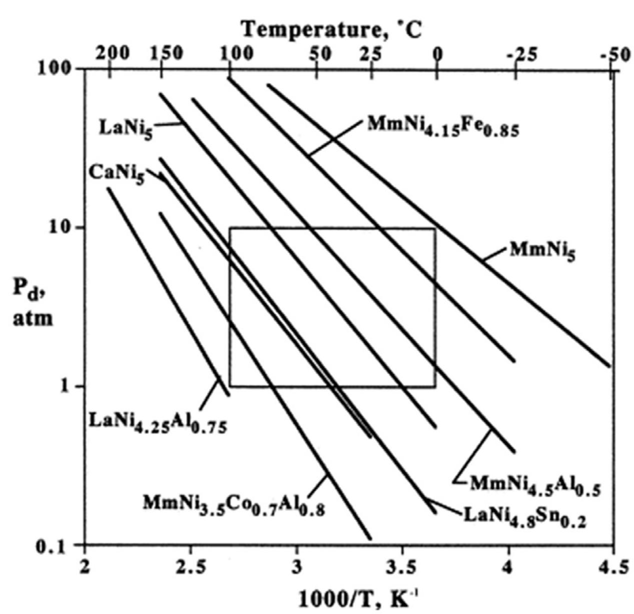

Fig. 3 – Van't Hoff plots for various AB_5 hydrides.

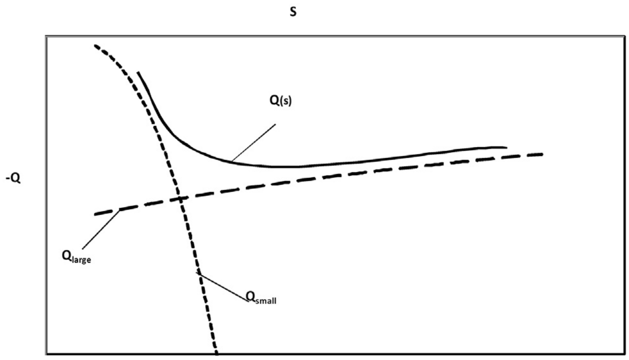

Fig. 4 – The ideal distance as the intersection of the Q_{large} and Q_{small} asymptotes.

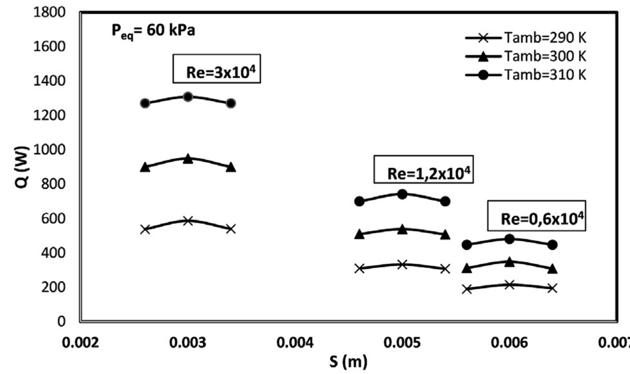

Fig. 5 – Variation of the heat transfer according to Reynolds number and ambient temperature for P_{eq} = 60 kPa.

distance for greatest rate of heat transfer. Heat transfer rate is formulated for the extreme distances that are large distance and small distance. Then, ideal distance is found by equalizing the formulas.

Consider a maximum distance, heat transfer rate for a tank can be written as

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

where the Nusselt number is defined as [22]:

$$Nu_D = 0,71 \cdot Re_D^{0,6} \cdot Pr^{0,36} \quad Re_D \geq 10^3 \tag{3}$$

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

In above equation, flow properties are defined by maximum velocity U_{max} that occurs within the staggered tank configuration, outer tank diameter D is taken as hydraulic diameter and υ is the viscosity at the film temperature ($T_f = (T_w - T_\infty)/2$).

The number of metal-hydride tanks in the bank of the cross-sectional plane is calculated by:

$$n = \frac{H\,W}{(S+D)^2 Cos30} \tag{4}$$

The heat transfer rate can be calculated by

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

$$q_{large} \cong 2,58 \frac{HLW}{(S+D)^2} k (T_w - T_\infty) \{Re_D^{0.6} \cdot pr^{0,36}\} \tag{6}$$

Consider a minimum distance, we are presuming tanks nearly touch. This solution method is known as Couett-Poiseulli flow. Because it solves flow in the small distance channel. The heat transfer rate can be calculated according to mass flow rate across tank banks ($\dot{m}$) by

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

$$q_{small} \cong \frac{1}{25} \rho \cdot C_p \cdot \nu \cdot \frac{W \cdot L}{H} \cdot Re_D^2 \cdot \left(S/_D \right)^3 \cdot (T_w - T_\infty) \tag{8}$$

To obtain maximum heat transfer rate, Eqs. (6) and (8) formulas are equalized and ideal distance S_{opt} is derived by the equalizing. Bejan et al. [33] and Sadeghipour et al. were used in relevant studies this method. [34].

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

The equation for optimized distance is obtained as below

Table 1 – Maximum Heat Transfer and Ideal distance According to Reynolds Number and Equilibrium Pressure for Different Ambient Temperatures.

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)
(T_{amb} = 290 K)							
120	289.0	0.006	−14	0.005	−21	0.003	−37
100	284.9	0.006	−81	0.005	−125	0.003	−219
60	274.1	0.006	−215	0.005	−333	0.003	−587
(T_{amb} = 300 K)							
120	289.0	0.006	−147	0.005	−227	0.003	−399
100	284.9	0.006	−214	0.005	−330	0.003	−582
60	274.1	0.006	−349	0.005	−539	0.003	−949
(T_{amb} = 310 K)							
120	289.0	0.006	−279	0.005	−430	0.003	−759
100	284.9	0.006	−346	0.005	−534	0.003	−941
60	274.1	0.006	−481	0.005	−742	0.003	−1308

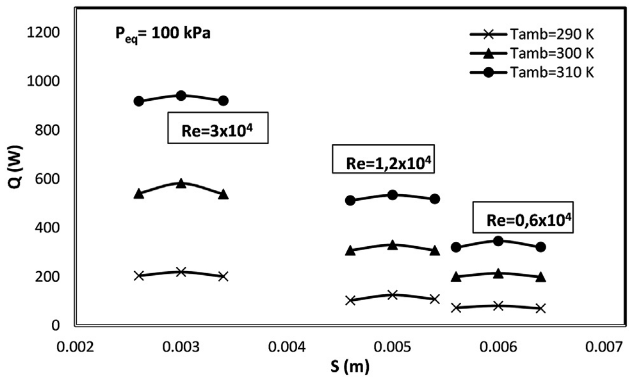

Fig. 6 – Variation of the heat transfer according to Reynolds number and ambient temperature for P_{eq} = 100 kPa.

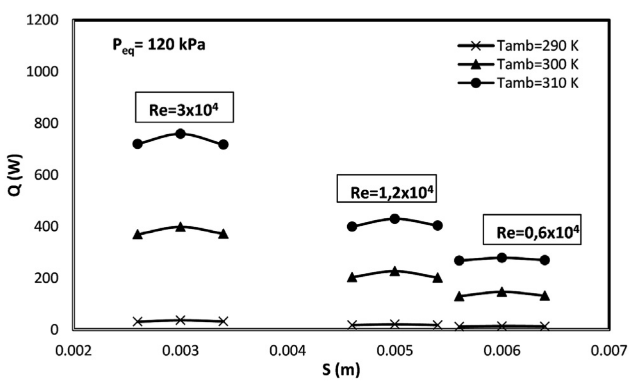

Fig. 7 – Variation of the heat transfer according to Reynolds number and ambient temperature for P_{eq} = 120 kPa.

$$\left(\frac{S_{opt}}{D}\right) \cong 4 \cdot Re_D^{-0.47} \cdot Pr^{-0.21} \tag{9}$$

The capacity of Maximum heat transfer is founded by inserting S_{opt} into Eq. (6) or Eq. (8).

The second step

The CFD analysis was run as two-dimensional. Temperature, velocity, pressure and slip/symmetry boundary conditions were applied to boundaries of the domain. Subsequently, relevant physics and material properties were applied to each domain using some simplifying assumptions to predict the heat transfer rates such as:

1. All of the analysis is under steady state.
2. No phase change and incompressible fluid.
3. Tanks have uniform surface temperature
4. Tanks exchange heat from lateral surfaces except for bottom and top of tanks.

Results and discussion

In our study, the outer diameter of metal hydride tank is 85 mm and the length of metal hydride tank is 400 mm for optimization procedure. The results obtained were determined for selected equilibrium pressures (i.e. 60 kPa, 100 kPa and 120 kPa) and ambient temperatures (i.e. 290 K, 300 K and 310 K). Because desorption process is endothermic conditioned air is flowed over the tanks at a mentioned temperature to provide required heat for desorption. Table 1 demonstrates that ideal distance and maximum heat transfer varies from ~0.003 to ~0.006 for selected parameters like pressures and temperatures. Also, results show that when the Reynolds number is rising, the

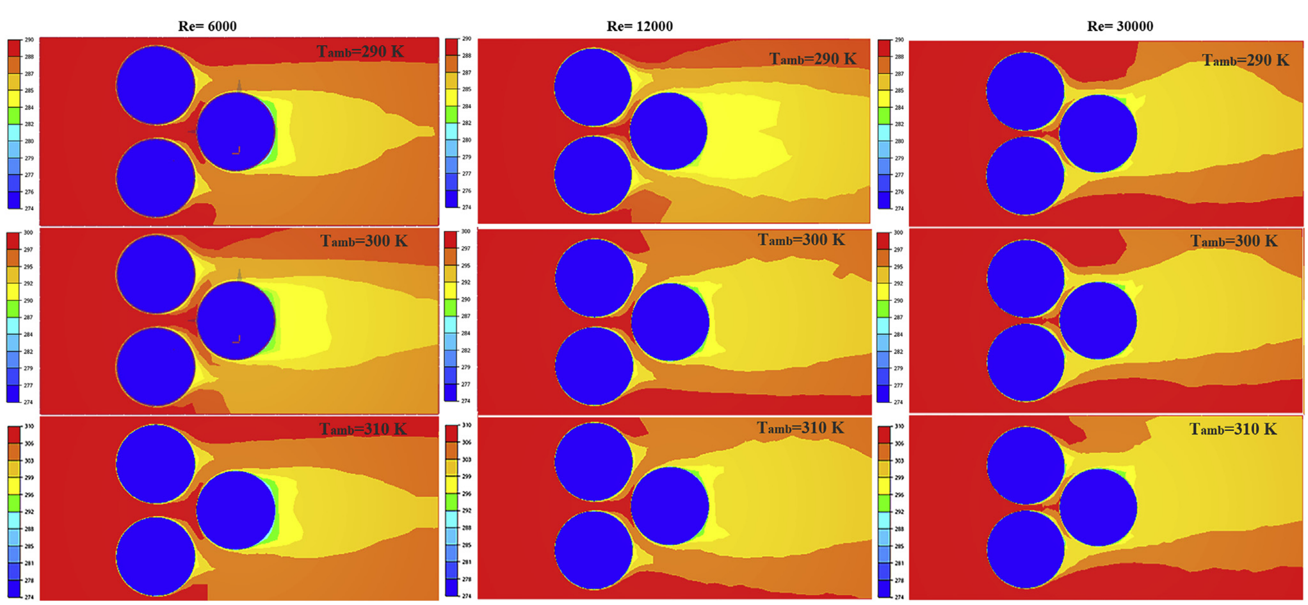

Fig. 8 – The profile of temperature on the surface of the horizontal tank arrays according to Reynolds number and ambient temperature for P_{eq} = 60 kPa.

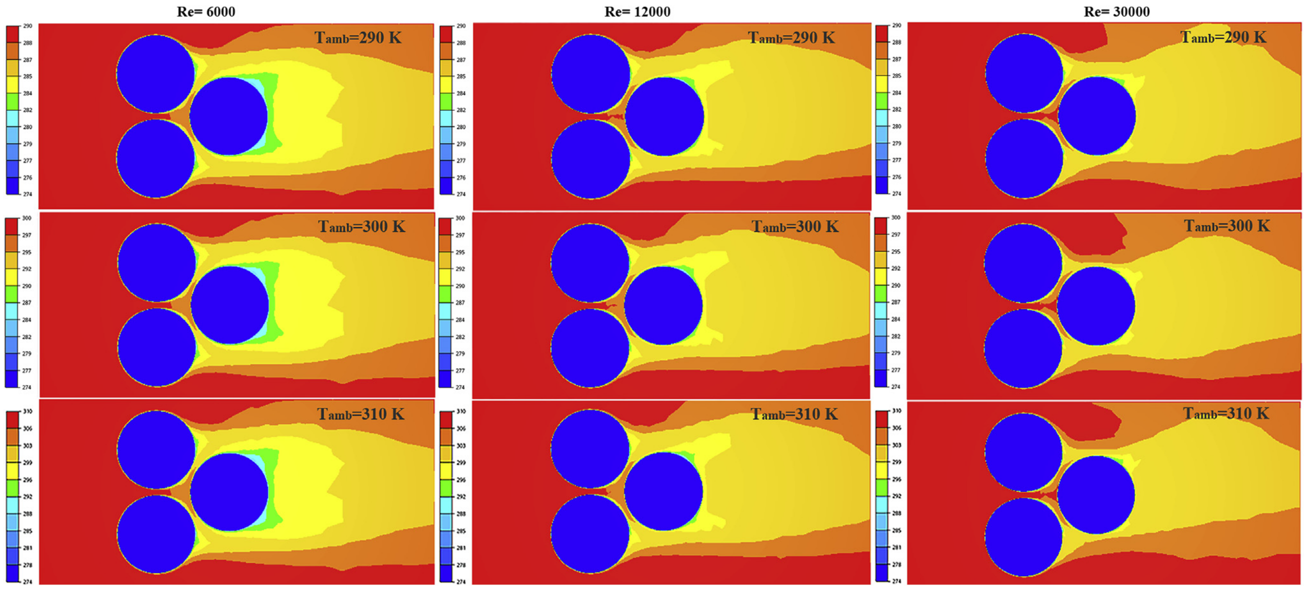

Fig. 9 – The profile of temperature on the surface of the horizontal tank arrays according to Reynolds number and ambient temperature for $P_{eq} = 100$ kPa.

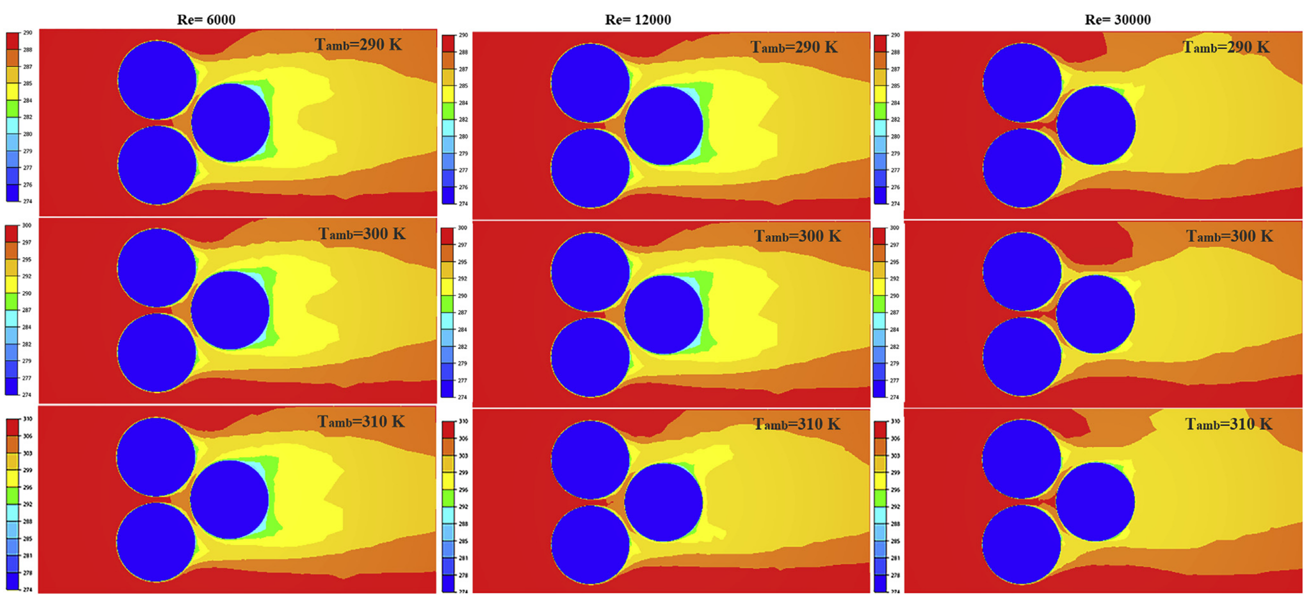

Fig. 10 – The profile of temperature on the surface of the horizontal tank arrays according to Reynolds number and ambient temperature for $P_{eq} = 120$ kPa.

distance will dramatically fall. It may be recognized that, lowest ideal distance occurs at Reynolds number of 3.0×10^4. Additionally, it may be observed the distance is not changing although equilibrium pressure of metal hydride is falling, and the ambient temperature is rising. For that reason, those parameters cannot affect the ideal distance, significantly. In addition to that, As the distance (S) is large or small than ideal distance, heat transfer falls. Finally, the ideal distance affects positively the total heat transfer tank arrangement.

Ideal distances for different Reynolds numbers and temperatures are shown in Figs. 5–7 according to selected Equilibrium pressures (60, 100 and 120 kPa). The heat-transfer curves as a function of distance shows how critical the distance is to obtain a maximum heat-transfer rate. The numerical results confirm the presence of a maximum as already observed in Figs. 5–7. Additionally, these plots show that heat transfer becomes maximum when the ideal distance is 3, 5 and 6 mm. Rising of ambient temperature triggers an increase in the heat transfer amount. It seems obviously that the heat transfer changes distinctly according to flow velocity for selected parameters. The results prove an ideal distance can be found. As a sample scenario, heat gain reaches maximum point, in comparison with the random distance, in distance of 3 mm at Re $= 3.0 \times 10^4$ as observed in Fig. 5.

Numerical simulations were solved by the computational method used in this study for the same geometry and simulation conditions. Figs. 8–10 show the distributions of temperature on around of the tanks for three T_{amb} and Reynolds number when P_{eq} equals to 60, 100 and 120 kPa, respectively. It is evident that the ambient temperature and Reynolds number are affecting this temperature distribution. The temperature near the tank surface was lower and increasing as it elongated in the downstream direction. The contours displayed in Figs. 8–10 reveal the temperature decreases in the fluid due to heat transfer to the tubes. The consequences of different Reynolds number to the fluid temperature distribution are shown in the above-said figures. As seen in figures, higher heat transfer rate was obtained from high Reynolds numbers. It can be observed that the front-located tanks have greater heat transfer for all conditions.

Comparing the temperature profiles obtained with CFD, it is found that the temperature distribution near the entrance region is almost same for all scenarios. The variation of air temperature along the gap between tanks and after is clearly seen in Figs. 8–10. The temperature profiles are different for $Re = 0.6$, 1.2 and 3×10^4 in the vicinity of the tanks surface. The air temperature is lower along the channel near the front-located tanks, also because of the increased airflow acceleration along those regions which it appears more apparent with distance. Thus, the temperature between the tanks surface for the ideal distance is distinctly lower than that in the corresponding region for the other distances. This leads to extra enhancement of the heat transfer from the tanks arrays at high Re number.

Numerical results confirm a heat gain of up to 13% in the ideal distances of 3, 5 and 6 mm.

Conclusion

This type of solid storage systems is mostly classified by reaction behavior related to charging and discharging of Hydrogen. Especially, reaction enthalpy strongly affects hydrogen storage capacity and efficiency. Because they depend on thermal management of reaction enthalpy that is proportional to heat. As a result, the management of heat is vital to obtain maximum benefit from stored Hydrogen. This work showed the importance of distance as surface area that affects the flow rate at which hydrogen gas can be extracted from tanks.

This study proves that if there is more than one tank, the ideal distance must be adjusted between tanks in an array of defined volume according to heat transfer mode. The ideal distance determined using the correlation of (9) corresponds to the maximum heat gain between tanks and ambient fluid. A numerical and computational study of the arrangement of metal hydride bank ($LaNi_5$) was carried out for three different equilibrium pressures and ambient temperatures. The study results showed that satisfactory enhancement in heat transfer occurs when the storage tank bank is arranged with suitable distance.

This study shows that this configuration satisfies required hydrogen flow rate due to maximum heat transfer. Also, usage of ideal distance enhances the hydrogen flow capacity of both charging and discharging. If the ambient fluid velocity can be increased, the ideal distance was decreased more than half. Moreover, although the equilibrium pressure and ambient temperature are changed, ideal distance has not affected. Finally, the results show that simultaneous parameters for maximum heat transfer might use to specify the need for optimization and encourage the development of a general numerical model concerning the arrangements of metal hydride tanks. Such optimized configuration in a global view might be of great importance for the design of metal hydride tanks and for the generation of flow structures in general such globally optimized configurations are expected to be of great importance for metal hydride banks design and for the generation of flow structures in general.

The simple benefits of this model are to provide easy utilization in placing. However, a best heat exchanger design is not enough to enhance the hydrogen flow capacity of both charging and discharging. On the other hand, the model proposed could be very effective to obtain higher Hydrogen capacity and faster kinetics in the design phase of metal hydride tank banks. The optimization approach accounts for the other geometrical configuration. It is simple enough to apply to integrated hydride tank – fuel cell systems to develop control systems and strategies. Moreover, in transport applications, like automobile and vehicles, the space is very important.

REFERENCES

[1] Arat HT, Surer MG. State of art of hydrogen usage as a fuel on aviation. Eur Mech Sci 2017;2(1):20–30.
[2] Afzal M, Mane R, Sharma P. Heat transfer techniques in metal hydride hydrogen storage: a review. Int J Hydrogen Energy 2017;42(52):30661–82.
[3] Briki C, Belkhiria S, Dhaou MH, Askri F, Jemni A. Dynamic study of a new design of a tanks based on metallic hydrides. Int J Hydrogen Energy 2018;43(3):1566–76.
[4] Mohammadshahi SS, Gray EM, Webb CJ. A review of mathematical modelling of metal-hydride systems for hydrogen storage applications. Int J Hydrogen Energy 2016;41(5):3470–84.
[5] Chibani A, Bougriou C. Effect of the tank geometry on the storage and destocking of hydrogen on metal hydride (LaNi5H2). Int J Hydrogen Energy 2017;42(36):23035–44.
[6] Mazzucco A, Dornheim M, Sloth M, Jensen TR, Jensen JO, Rokni M. Bed geometries, fueling strategies and optimization of heat exchanger designs in metal hydride storage systems for automotive applications: a review. Int J Hydrogen Energy 2014;39(30):17054–74.
[7] Shafiee S, McCay MH. Different reactor and heat exchanger configurations for metal hydride hydrogen storage systems – a review. Int J Hydrogen Energy 2016;41(22):9462–70.
[8] Bhogilla SS. Design of a AB2-metal hydride cylindrical tank for renewable energy storage. J Energy Storage 2017;14(Part 1):203–10.
[9] Veerraju C, Gopal MR. Heat and mass transfer studies on elliptical metal hydride tubes and tube banks. Int J Hydrogen Energy 2009;34(10):4340–50.
[10] Bhouri M, Goyette J, Hardy BJ, Anton DL. Numerical modeling and performance evaluation of multi-tubular sodium alanate hydride finned reactor. Int J Hydrogen Energy 2012;37(2):1551–67.
[11] Johnson TA, Kanouff MP, Dedrick DE, Evans GH, Jorgensen SW. Model-based design of an automotive-scale,

metal hydride hydrogen storage system. Int J Hydrogen Energy 2012;37(3):2835–49.
[12] Raju M, Kumar S. Optimization of heat exchanger designs in metal hydride based hydrogen storage systems. Int J Hydrogen Energy 2012;37(3):2767–78.
[13] MacDonald BD, Rowe AM. Impacts of external heat transfer enhancements on metal hydride storage tanks. Int J Hydrogen Energy 2006;31(12):1721–31.
[14] Jemni A, Nasrallah SB. Study of two-dimensional heat and mass transfer during absorption in a metal-hydrogen reactor. Int J Hydrogen Energy 1995;20(1):43–52.
[15] Aldas K, Mat MD, Kaplan Y. A three-dimensional mathematical model for absorption in a metal hydride bed. Int J Hydrogen Energy 2002;27(10):1049–56.
[16] Bao Z, Wu Z, Nyamsi SN, Yang F, Zhang Z. Three-dimensional modeling and sensitivity analysis of multi-tubular metal hydride reactors. Appl Therm Eng 2013;52(1):97–108.
[17] Bao Z, Yang F, Wu Z, Nyamsi SN, Zhang Z. Optimal design of metal hydride reactors based on CFD–Taguchi combined method. Energy Convers Manag 2013;65:322–30.
[18] Cho J-H, Yu SS, Kim MY, Kang SG, Lee YD, Ahn KY, et al. Dynamic modeling and simulation of hydrogen supply capacity from a metal hydride tank. Int J Hydrogen Energy 2013;38(21):8813–28.
[19] Minko KB, Artemov VI, Yan'kov GG. Numerical simulation of sorption/desorption processes in metal-hydride systems for hydrogen storage and purification. Part I: development of a mathematical model. Int J Heat Mass Tran 2014;68:683–92.
[20] Minko KB, Artemov VI, Yan'kov GG. Numerical simulation of sorption/desorption processes in metal-hydride systems for hydrogen storage and purification. Part II: verification of the mathematical model. Int J Heat Mass Tran 2014;68:693–702.
[21] Ma J, Wang Y, Shi S, Yang F, Bao Z, Zhang Z. Optimization of heat transfer device and analysis of heat & mass transfer on the finned multi-tubular metal hydride tank. Int J Hydrogen Energy 2014;39(25):13583–95.
[22] Nakano A, Ito H, Bhogilla SS, Motyka T, Corgnale C, Greenway S, et al. Research and development for a metal hydride tank with double coil type heat exchanger below 1.0 MPa (G) operation. Int J Hydrogen Energy 2015;40(6):2663–72.
[23] Dhaou H, Khedher NB, Mellouli S, Souahlia A, Askri F, Jemni A, et al. Improvement of thermal performance of spiral heat exchanger on hydrogen storage by adding copper fins. Int J Therm Sci 2011;50(12):2536–42.
[24] Satya Sekhar B, Lototskyy M , Kolesnikov A, Moropeng ML, Tarasov BP, Pollet BG. Performance analysis of cylindrical metal hydride beds with various heat exchange options. J Alloy Comp 2015;645(Suppl. 1):S89–95.
[25] MacDonald BD, Rowe AM. A thermally coupled metal hydride hydrogen storage and fuel cell system. J Power Sources 2006;161(1):346–55.
[26] Førde T, Eriksen J, Pettersen AG, Vie PJ, Ulleberg Ø. Thermal integration of a metal hydride storage unit and a PEM fuel cell stack. Int J Hydrogen Energy 2009;34(16):6730–9.
[27] Rizzi P, Pinatel E, Luetto C, Florian P, Graizzaro A, Gagliano S, et al. Integration of a PEM fuel cell with a metal hydride tank for stationary applications. J Alloy Comp 2015;645(Suppl. 1):S338–42.
[28] Tetuko AP, Shabani B, Andrews J. Thermal coupling of PEM fuel cell and metal hydride hydrogen storage using heat pipes. Int J Hydrogen Energy 2016;41(7):4264–77.
[29] Jiang Z, Dougal RA, Liu S, Gadre SA, Ebner AD, Ritter JA. Simulation of a thermally coupled metal-hydride hydrogen storage and fuel cell system. J Power Sources 2005;142(1–2):92–102.
[30] Hilali I. Optimum spacing between horizontal metal hydride (MH) hydrogen storage tanks integrated with fuel cell power system in natural convection. J Therm Sci Technol 2015;35(2):129–36.
[31] Stanescu G, Fowler AJ, Bejan A. The optimal spacing of cylinders in free-stream cross-flow forced convection. Int J Heat Mass Tran 1996;39(2):311–7.
[32] Sandrock G. A panoramic overview of hydrogen storage alloys from a gas reaction point of view. J Alloy Comp 1999;293–295:877–88.
[33] Bejan A. Convection heat transfer. New York: Wiley; 1984.
[34] Sadeghipour MS, Razi YP. Natural convection from a confined horizontal cylinder: the optimum distance between the confining walls. Int J Heat Mass Tran 2001;44(2):367–74.