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Enhancement of Hydrogen Storage Process Using Heat Pipe

Fawzi Ali Elhamshri [1,*], Mohamed Ahmed Aissa[2], Salahldin Ali Uallus[3]

[1]*Chemical Engineering Department, Faculty of Engineering - Algaraboli, Elmergib University*
elhamshrifawzi@gmail.com
[2] *Chemical Engineering Department, Faculty of Engineering - Algaraboli, Elmergib University*
missa@gmail.com
[3]*Mechanical Engineering Department, Faculty of Engineering – Alzawia University*
salahuallus@yahoo.com

ABSTRACT

Heat transfer from/to the metal hydride bed is a critical factor affecting the performance of metal hydride storage tanks (MHSTs for short). This study examined the effect of heat pipe on the metal hydride tank by means of heat management. The experimental study explains the use of heat pipe for enhancement the heat transfer in MHSTs, which built using $LaNi_{4.75}Al_{0.25}$ as the storage media and under various hydrogen pressure supply in the range of 2 to10 bar. This study also presents comparisons between the two different MHSTs which are designed with and without heat pipe. Two configurations of metal hydride tanks are considered and consisted of tubular cylindrical tanks with same base dimensions. The first one is a closed cylinder that exchanges heat through its lateral and base surfaces by means cool with natural convection. Heat pipe is made of copper–methanol combination and situated along the axis of the second reactor. Results show that the usage of heat pipe can be a good choice to increase hydrogen storing performance. The absorption time at 10 bar hydrogen inlet pressure was reduced more than 30%, and the mass of hydrogen storage increased by approximately 10% - 15%.

Keywords
Hydrogen storage,
Heat pipe,
Metal hydride, Absorption time, Storage rate.

*Corresponding Author Email: elhamshrifawzi@gmail.com

1. INTRODUCTION

The reduction of fossil fuel resources and its energy consumption contamination have make a clear request for an alternative energy sources [1].Hydrogen is new clean energy and the best substitution for fossil fuels due to its great calorific value and advantages in safety and reliability [2]. However, the whole studies on hydrogen energy have shown the problem of hydrogen storage which reduces its use. Recently, MHSTs which can store large amounts of hydrogen in small volumes and at high pressure levels, have attracted several attention. However, heat management in the hybride bed is the main concern for MHSTs design as a result of kinetic reactions, heat and mass transfer, which consider to be the key factors on hydrogen charging/discharging process. Therefore, there have been numerous experimental and theoretical studies on several aspects of hydrogen storage.

Demircan et al. 2005 experimentally studied the hydrogen absorption in two $LaNi_5$-H_2 tanks, and developed a 2-D theoretical model to investigate the thermal and kinetic characteristics of the hydriding process. They found successful heat removal design guides to reduce the hydrogen storing time. [3]. Kaplan 2009 investigated the effects of heat transfer mechanisms in the charging process for different tank configurations. The experimental results showed that, the hydrogen charging to the MHSTs was mainly heat transfer-dependent and the tank which has a better cooling condition exhibited the fastest charging characteristics under all specific values of hydrogen pressure [4]. Dhoau et al. 2010 and 2011 studied the influence of different tank configurations, and the effects of operating parameters on the reaction time of hydrogen in MHSTs. The experimental results show that, the storage time is clearly reduced by using a finned spiral coiled heat exchange system with a good choice of design study parameters [5, 6]. Jemni et al. and Ben Nasrallah's 1999 presented anexperimental setup and technique to determine the controlling characteristics in $LaNi_5$–H_2 system. An agreement of numerical and experimental data is obtained [7]. The mathematical model by Jemni and Ben Nasrallah's 1999 was extended and upgraded to three-dimensional model by Mat and Kaplan 2002 in order to analysis heat and mass transfer in a metal-hydride bed [8]. Mellouli et al. 2007 and 2009 investigated the performance of various MHST configurations and the influence of several parameters. The obtained results showed that, the hydrogen storing time is reduced by using spiral coiled tube heat exchanger with a good choice of design study parameters. An agreement of numerical and experimental data is obtained and the proposed model found to be effectively useful for the metal-hydride storage tank design [9, 10]. Souahlia et al. 2011 investigated the influence of several parameters, e.g.; (hydrogen inlet design, input pressure, and cooling/heating fluid temperature) on the performance of various metal-hydride storage tank configurations. The experimental results showed that, the successful heat removal design guide to reduce the hydrogen storing time with a good choice of design study parameters [11, 12]. Chung 2013 investigated the heat transfer mechanism on MHSTs with and without heat pipe. The experimental results showed that, the heat pipe is a useful way to improve hydrogen storage capacity. More than half time reduced for absorption process, and 44% of the time increased at 1 L/min hydrogen flow rate for desorption process [2]. Kayfeci 2014 investigated the heat transfer mechanism on MHSTs under charged hydrogen pressure in a range of (2–8 bars). The obtained results showed that, the using of metal-hydride storage design tank with fins confirms the less charging time [13]. The heat exchanger is a successful technique to develop MHSTs. Heat exchangers are used in hydrogen storage processes to accelerate the heat transfer rate in the metal hydride [4, 9, 10, 14-24]. Askri et al. 2009 indicated that approximately 80% improvement of the charging time can be reached when the design included a concentric heat exchanger tube equipped with fins and packed with flowing cooling fluid [15]. The adding fins to a heat exchanger present a significant solution to improve the hydriding process. $LaNi_xAl_{5-x}$ is considered to be a very useful material for hydrogen absorption because of its low plateau pressure and the resistance to impurities in hydrogen gas. It was also found that the partial replacement of Ni in $LaNi_5$ alloy by a small amount of Al resulted in a prominent increase in the cycle lifetime without causing much decrease in hydrogen absorption capacity and in minimizing corrosion attack of the hydride electrode [2]. Heat pipe is a device with very high thermal conductance. This study presents a pilot design for a metal hydride tank equipped with a heat pipe to test the concept. In experimental studies, 2-10 bars of hydrogen charge pressures are adjusted for each vessel, and the thermocouples are positioned at 3 points on tanks and temperature distributions along the vessels are measured. In addition, the heat pipe temperature and stored hydrogen mass are determined.

2. EXPERIMENTAL WORK

2.1 Tank Design

Figure 1 shows the geometries of two MHSTconfigurations designed for this study.

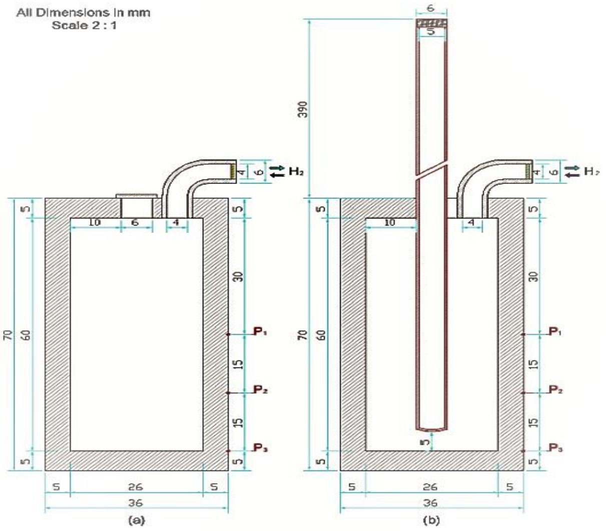
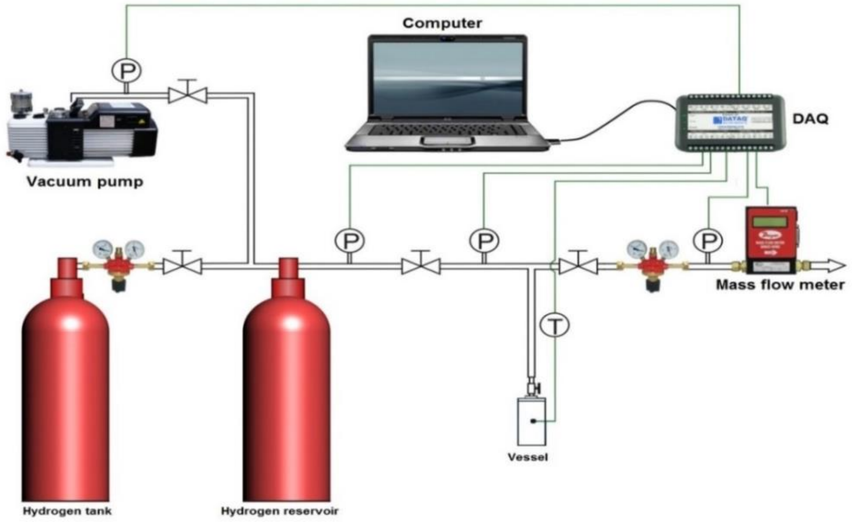


Figure*1.Cross section of MHSTs. a) Without heat pipe, b) With heat pipe.*

Both tanks are made ofAISI 316 stainless steel, and have the same inner and outer diametersof 26 mm and 36mm, respectively, and the same inner heightof 60 mm. A heat pipe is made of a copper–methanol combination situated along the axis of the second tank shown in (Figure 1b). The heat pipe inner diameter and thickness are 5 mm and 1mm, respectively, with 450 mm length. The temperature in the hydride bed is monitored by three thermocouple probes (P_1, P_2, and P_3) for each tank. All thermocouple probes located outside the tank on the external wall surface at the height of 5 mm, 20 mm and 35 mm for P_3, P_2 and P_1 respectively. All thermocouple probesare attached to the exterior of the tank using metal foil tape to measurethe external wall temperature. The vessels consist of a cylindrical container that exchanges heat through the surfaces (bottom and sides). The tanks are filled with a powder of $LaNi_{4.75}Al_{0.25}$ material with a mass of 90 gm at approximately 70% rate and charged with hydrogen. A free space is left to take into account of $LaNi_{4.75}Al_{0.25}$ expansion after the absorption of hydrogen gas (30% of the total volume). The powder size in this study is between 75 and 150 µm. A 0.5µm grade tubular filter is fixed at the inlet/outlet tubing to prevent metal powders from being drawn out during the discharging process.

2.2 Experimental Equipment and Set-Up

Figure 2 shows the schematic of the experimental equipment. The experimental set-up is done in order to determine the reaction speed, the amount of hydrogen stored and the hydrogen absorption features of a metal hydride on $LaNi_{4.75}Al_{0.25}$ alloy. In the assembly; a design tank, a mechanical grinder with steel ball for producing tiny particles, a vacuum pump for removing the moisture and the air inside the reactor before the experiments, a ceramic resistance for evaporating the moisture and air remained inside the reactor, manometers, thermocouples, data collecting system, a regulator for adjusting the hydrogen pressure, a tank containing hydrogen with 99.999 % of purity exist. In experimental studies two tanks were used separately, the first one is without heat pipe and the second is with a heat pipe.



Figuer2. Experimental set-up

2.3 EXPERIMENTAL PROCEDURES

$LaNi_{4.75}Al_{0.25}$ material grinded with 900 rpm grinder speed inside the mechanical grinder associated with steel ball at the rate of 1/10 for 30 minutes until meet a size between 75 and 150 µm, before the powders were put into the designed storage tank. 90 gmof $LaNi_{4.75}Al_{0.25}$ powder is filled at the rate of 70% of tank volume. The tank is settled in ceramic resistance by being assembled to the vacuum pump at a low pressure. The tank heated to approximately 200-250 °C and vacuumed for 20 minutes. After this operation, the reactor assembled to the hydrogen cylinder in order to be able to make the activation operation possible and charged under 10 bar hydrogen pressure. These operations are repeated 8 times to reach the full activation operation for both MHSTs. Activation is required to start any hydriding/dehydriding process and very important for the real applications of MHSTs, on account of, the oxide is usually covered the surface of metals and act as a passive film [13]. When the activation processis completed, experimental operations take place.Three thermocouple probes settled at the locations of 5, 20 and 35 mm along the z axis for both MHSTs (Figure 1). Temperature scanning device and sensitive scales are connected to the computer via data recording cables. Hydrogen charge pressure adjusted to different pressure range, e.g. (2, 4, 6, 8 and 10bar) by means of a pressure regulator. The tank, without heat pipe started first. For the absorption case, the temperature within the tank increases at the beginning, due to hydrogen metal reaction is exothermic, and then decreases progressively with the reaction kinetics decay. As the tank temperature decreases to the room conditions, the time interval necessary to saturate the tank is recorded and found to be 4000s approximately. In order to study the inlet hydrogen pressure effect on the temperature evolution within the tank, the hydrogen absorption experiment is realized for five different pressure values (2, 4, 6 8 and 10 bar). The temperature (T_f) of the cooling fluid around the tank is kept constant at ~20 ^{o}C. After the experiments finished for the tank without heat pipe, the tank with heat pipe started with activation operation and, then the experiments repeated at 2, 4, 6, 8 and 10 bar pressure at the same conditions with those of the heat exchange without heat pipe for the same amount of time interval. For the desorption case, the metal-hydrogen reaction is endothermic, the opposite phenomena takes place.

3. RESULTS AND DISCUSSION

The experiments in this study are carried out to evaluate the efficiency of two hydrogen storage tank configurations; without heat pipe (Figure 1a), and by using a heat pipe (Figure 1b). In view of practical applications, a solid-state hydrogen storage tank should be able to complete hydrogen charge in a short enough time while keeping stable discharge rates for a long enough time. The hydride process in metals is closely related to heat management. The hydride bed needs to control temperature and to be cooled to recompense for the heat released by the exothermic hydriding process. Therefore, evaluations of the absorption performance for the metal hydride storage tanks with and without heat pipe are presented, focusing on the charge time and the temperature distribution in the MHSTs.

Figure 3 shows the temperature profiles of metal hydride bed during the hydriding process for the storage tank without heat pipe at both of 4 and 10 bar pressure. For example; the P_2 position maximum temperature is reached in the duration of approximately 300 s at each pressure values, and then the reaction rate decreased and started to fall. Moreover, the reaction temperature has come to room temperature (~20 °C) at the end of 4000 seconds. The maximum temperature is held at 10 bar pressure; while the reaction pressure reduced, the temperature has decreased. Furthermore, when the pressure increases, the amount of hydrogen stored increased by increasing the exothermic reaction. The hydrogen charge time requiredat

P_2 position in the tank when 4, and 10 bar pressure values applied are 292, and, 210 s respectively, while the temperatures are 73.42°C, and 83.93 °C respectively. Figure 4 shows the temperature profiles of metal hydride bed during the hydriding process for the storage tank with heat pipe at both of 4 and 10 bar pressure. In the P_2 position, maximum temperature is reached in the duration of approximately 200 s under each pressure values, and then the reaction rate decreased and started to drop. The hydrogen charge time requiredat P_2 position in the tank when 4 and 10 bar pressure values applied are 79, and, 137 s respectively, while the temperatures are 67.17 °C, and 78.92 °C measured respectively during this period.

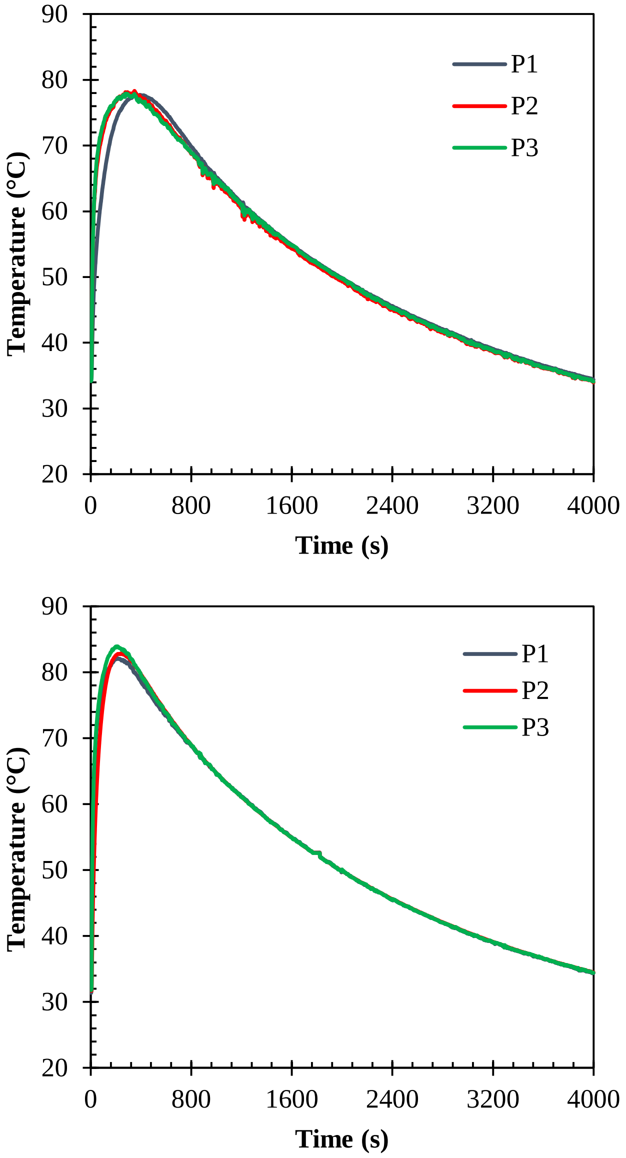


Figure 3. Temperature profiles of metal hydride bed during the hydriding process for the storage tank without heat pipe at a) 4 bar on the left and b) 10 bar on the right.

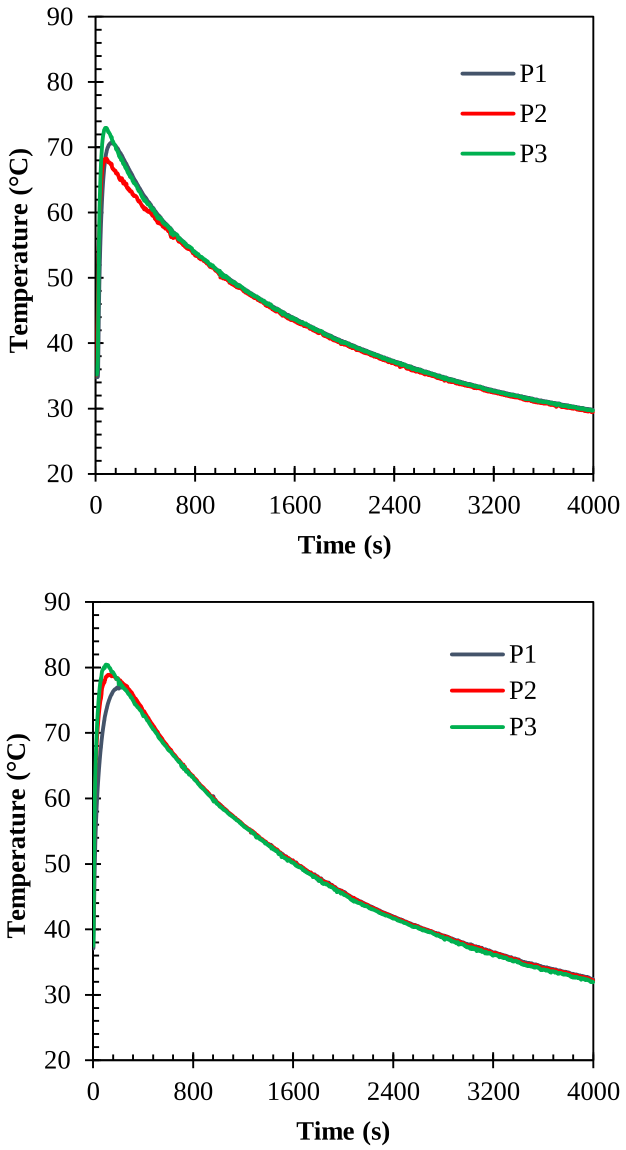


Figure 4. Temperature profiles of metal hydride bed during the hydriding process for the storage tank with heat pipe at a) 4 bar on the left and b) 10 bar on the right..

From (Figurs 3 and 4), it is clearly observed that the temperature in the tank is higher when the hydrogen inlet pressure is important, which results in a higher absorption rate and shorter storage time. This is due to the reaction acceleration which corresponds to an increase of the heat quantity released. The time needed for the tank saturation is smaller when the hydrogen inlet pressure is higher. Consequently, we note that the time at which approximately 1.3%wt hydrogen stored is approximately 200 s for the vessel with heat pipes as shown in (Fig. 4), while approximately 300 s is required for the vessel without heat pipe as shown in (Figure 3). It is clear from the figures that, for 4 bar supply pressure, the maximum temperature reaches 73.42 °C for the tank without heat pipe and 67.17 °C for the tank with heat pipes. As well as;

for 10 bar supply pressure, the maximum temperature reaches 83.93 °C for the tank without heat pipe and 78.93 °C for the tank with heat pipes. This explains the improvement of the absorption kinetics observed for the configuration of using heat pipe as a cooling system. Indeed, due to the exothermic character of the absorption reaction, the charging of MHSTs is mainly heated transfer-dependent and the vessel with better cooling exhibits the fastest charging characteristics.

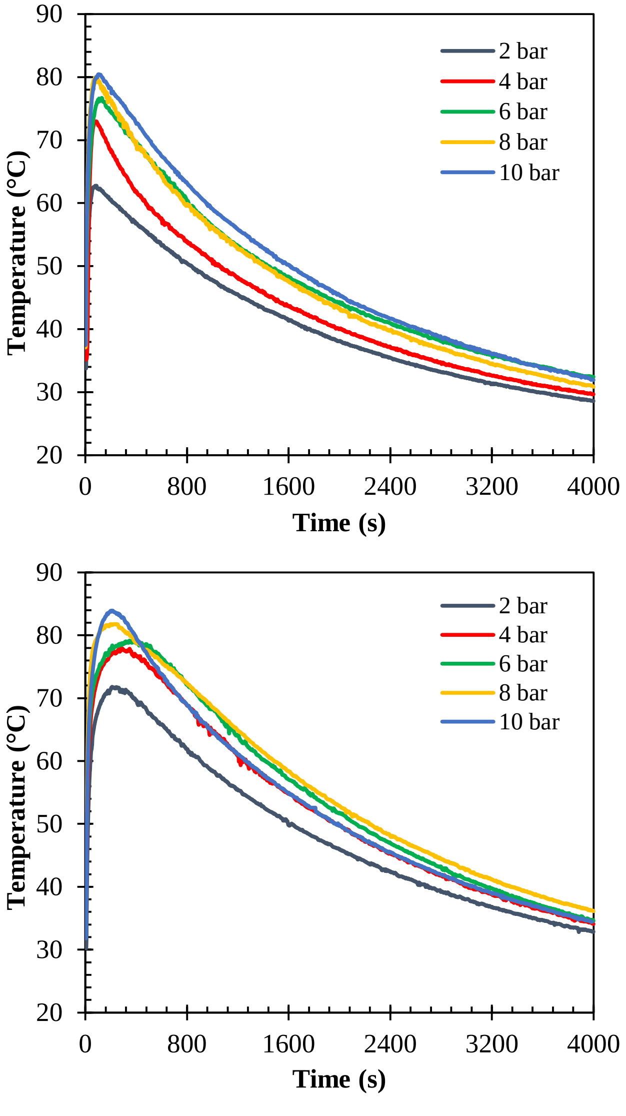


Figure 5. Effect of the initial hydrogen pressure on the average bed temperature, a) with heat pipe on the left and, b) w/o heat pipe on the right

The temperature change with an access time at different positions and the different charge pressure of hydrogen with and without heat pipes is given in Figure 5. The measured temperatures on the tank configuration with a heat pipe during charging at the different hydrogen pressures are shown in (Figure 5a). The hydrogen charge time required at P_2 position in the tank when 2, 4, 6, 8, and 10 bar pressure values supplied are 79, 83, 129, 101, 137 s respectively, while the temperatures are 67.17, 72.98, 76.64, 79 and 78.92 °C respectively. It is observed that the tank temperature increases as the pressure of the supplied hydrogen increases due to the enhanced kinetics of theexothermic hydrogen absorption reaction with the pressure. Furthermore, the temperature variation of the tank configuration without heat pipe during charging of different hydrogen pressures is shown in (Figure 5b). The hydrogen charge time requiredat P_2 position in the tank when 2, 4, 6, 8, and 10 bar pressure values supplied are 292, 291, 347, 256, 210 s respectively, while the temperatures 73.42, 78.12, 81.63, 82.94 and 83.93 °C measured respectively during this period.It is observed that the vessel temperature increases as the pressure supply of hydrogen increases. However, the maximum temperatures are higher than that of the tank with heat pipes. This can be attributed to enhanced heat transfer due to the heat pipe. Also, the time to reach maximum temperature in all cases is lower than that in the case of the vessel without heat pipe, indicating faster hydrogen charging because of the enhanced reaction kinetics as a result of better heat removal from the reactor by means of heat pipes. The tank configuration with heat pipe shows the most rapid charging with the lowest temperature increase due to betterheat removal from the vessel.

It is recognized that the high hydrogen charge rate was near the tank walls. Therefore, the temperature reached the maximum values in this region at the begging with comparison to moving along the z axis in the tank. The temperature profile versus an access time on the heat pipe at the z axis in the tank is given in Figure 6. The access times of 128, 148, 156, 116, 146 s under the different hydrogen supply pressure,e.g.; 2, 4, 6, 8 and 10bar are observed and the maximum temperatures recorded were: 44.84, 51.64, 63.35, 70.19, 71.63°C respectively.

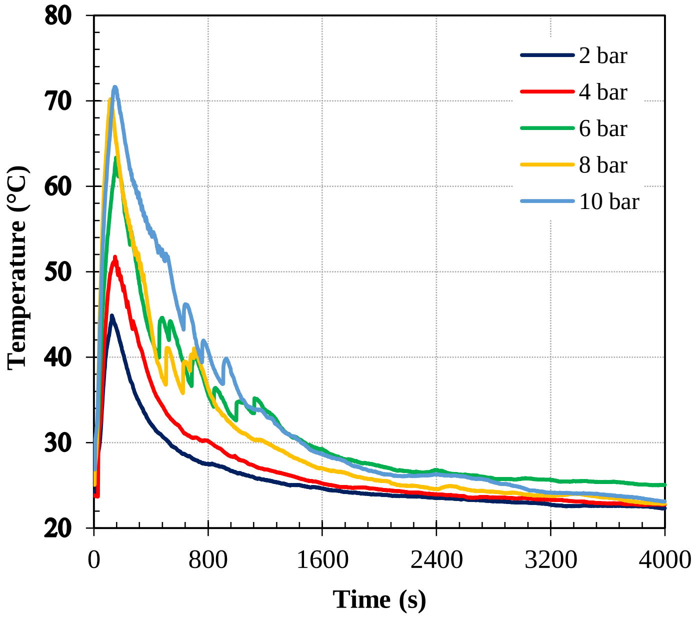


Figure 6. The temperature changes due to the different pressures on heat pipe.

The amount of hydrogen stored by the tank type and pressure is given in Figure 7. It is clearly observed that the amounts of hydrogen stored in the designed tank without heat pipe at the different supply pressure, e.g. (2, 4, 6, 8, and 10 bar) are 0.61, 0.62, 0.77, 0.79 and 0.80 gm. Moreover, the amount of hydrogen stored in the designed tank with heat pipe for the different supply pressure, e.g. (2, 4, 6, 8, and 10 bar) are 0.69, 0.74, 0.78, 0.90 and 0.95 gmrespectively.The hydrogen absorption kinetic is improved by using the heat pipe configuration vessel and more hydrogen was stored during the experience.

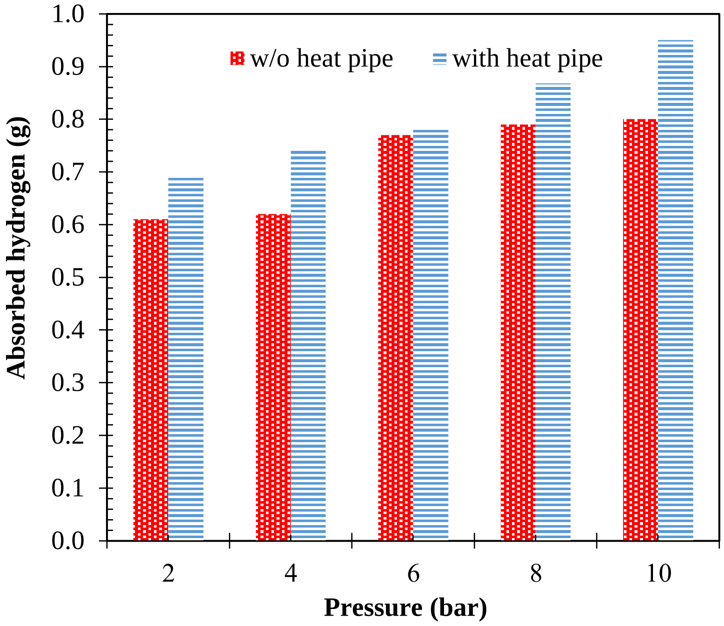


Figure7.Effect of the initial hydrogen pressure on the absorption kinetics.

4. CONCLUSION

This study presents a novel design for a metal hydride tank equipped with a heat pipe, and built using $LaNi_{4.75}Al_{0.25}$ as the storage media to show the development of hydrogen storage efficiencyusing a heat pipe.Two configurations of metal hydride tanks are considered and consisted of tubular cylindrical tanks with same inner volume and base dimensions. The first one is a closed cylinder that exchanges heat through its lateral and base surfaces by means cool with natural convection. Heat pipe is made of copper–methanol combination and situated along the axis of the second tank. The influences of the heat pipe to the heat transfer and the reaction kineticcharacteristics have been investigated. Temperature measurements have been recorded at the different locations on external wall surface for both tanks, under various hydrogen pressure supplies in the range of 2 to10 bar in order to verify thetemperature profiles for both tanks. In addition, the mass of hydrogen stored has been recorded. This study also presents comparisons between the two considered tanks. Accordingly, the heat released during charging process has been removed quicklyin case of the tank with a heat pipe, and thus the temperature values reduced compared to the tank without heat pipe. It is observed that the tank temperature increases as the supply pressure of hydrogen increases due to the enhanced kinetics of the exothermic hydrogen absorption reaction, and recognized that the high hydrogen charge rate was near the tank walls at the regions closer to the hydrogen inlet. Therefore, the temperature reached the maximum values in this region at the begging with comparison to moving along the z axis in the tank.The time duration to reach the maximum temperatures arereduced by using the heat pipe.Hence, results show that the use of heat pipe can be a good way to increase hydrogen storing. The absorption time at 10 bar hydrogen supply pressure was reduced more than 30%, and desorption time of hydrogen flow rate increased 10% - 15%.

ACKNOWLEDGMENT

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تعزيز عملية تخزين الهيدروجين باستخدام أنبوب الحرارة

فوزي علي محمد الهمشري[1]،* ، محمد أحمد عيسي[2] ، صلاح علي العلوص[3]

[1] قسم الهندسة الكيميائية ، كلية الهندسة القره بوللي ، جامعة المرقب، *elhamshrifawzi@gmail.com*
[2] قسم الهندسة الكيميائية ، كلية الهندسة القره بوللي ، جامعة المرقب، *missa@gmai.com*
[3] قسم الهندسة الميكانيكية ، كلية الهندسة ، جامعة الزاوية، *salahuallus@yahoo.com*

الملخص

في عمليات تخزين الهيدروجين ، يعد نقل الحرارة من/إلى طبقة هيدريد المعدن عاملاً بالغ الأهمية يؤثر على أداء صهاريج تخزين الهيدروجين. فحصت هذه الدراسة تأثير الأنبوب الحراري على خزانات هيدريد المعدن ، والتي تم بناؤها على أساس تباين في نزع حرارة الخزان. . هذه الدراسة التجريبية تشرح استخدام أنبوب الحرارة لتعزيز نقل الحرارة تحت تأثير ضغط هيدروجين مختلف يتراوح من 2 إلى 10 بار. تم في هذه الدراسة مقارنة نموذجان من صهاريج تخزين الهيدروجين تتكون من خزانات أسطوانية بنفس أبعاد القاعدة. الأول عبارة عن أسطوانة مغلقة تتبادل الحرارة من خلال أسطحها الجانبية والقاعدية عن طريق التبريد بالحمل الحراري الطبيعي. والثاني يتكون من اسطوانة مماثلة تنزع منها الحرارة عن طريق أتبوب حراري مصنع معمليا من النحاس بداخله سائل الميثانول مثبت على المحور بمنتصف الخزان. تظهر النتائج أن استخدام أنبوب الحرارة يمكن أن يكون خيارًا جيدًا لزيادة أداء تخزين الهيدروجين. تم تقليل وقت الامتصاص للهيدروجين عند استخدام 10 بار ضغط بأكثر من 30٪، وزادت كتلة تخزين الهيدروجين بحوالي 10٪ - 15٪.

الكلمات الدالة:
تخزين الهيدروجين.
أنبوب الحرارة.
هيدريد المعدن.
وقت الامتصاص.
معدل التخزين.

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[*] البريد الإلكتروني للباحث المراسل: *elhamshrifawzi@gmail.com*