Energy Management of a Metal Hydride Hydrogen Storage Tank Using a Loop Heat Pipe

Lucia Martvoňová[1,*], *Milan* Malcho[1], *Jozef* Jandačka[1], and *Ladislav* Ďuroška[1]

[1]University of Zilina, Faculty of mechanical engineering, Department of power engineering, Univerzitná 8215/1 01026, Zilina, Slovakia

Abstract. The article analyzes the thermal management of a metal hydride storage tank for hydrogen in the mode of filling the storage tank with hydrogen when it is necessary to cool the metal hydride filling intensively. Cooling is carried out by boiling water at low pressure and therefore also at low temperatures of around 50 °C. In the article, a heat transfer model during boiling is developed and the limits of heat transfer during boiling at low temperatures are determined.

Keywords: *metal hydride, hydrogen, loop heat pipe, energy management*

1 Introduction

Storing hydrogen in storage tanks with metal hydrides is less energy-intensive than storing hydrogen in a liquid state. Thus, the reservoirs do not have to meet the demanding conditions of low temperatures and high pressure, and minimal heat losses. The storage of hydrogen in metal hydrides, however, requires compliance with the specified temperature conditions and the need for removal or supply of heat when storing or obtaining hydrogen from the metal hydride [1].

The reservoir usually consists of individual segments with metal hydride, including a pipe with a cooling medium. Heat transfer in the hydride takes place only by conduction through the wall of the tube in which it is stored, into the volume of the hydride. On the outer wall, heat is transported by convection from or to the heat-carrying medium. More advanced methods of construction use an increase in the heat exchange surface with ribs. In this case, the metal hydride is placed between the fins, while the cooling medium flows inside the tube. The hydrogen flows into the hydride through a separate pipe that is routed under the cooling pipe. For mobile devices, the storage tank is heated by external heating during filling. Cooling is provided by forced convection while driving. There are ribs in the volume of the metal hydride, which ensure the conduction of heat from the outer shell to the inner volume [2].

In another construction solution [3], there are several separate reservoirs with metal hydride, which are connected by pipelines into one block fixed in a rigid casing, in which the pipeline for the supply or removal of heat is also placed. These separate reservoirs are subsequently also covered with lead. The main parameter that affects the possibilities of deploying such containers is the weight of the entire assembly. The disadvantage of such a solution is the low heat removal from the metal hydride only by free convection. Therefore,

* Corresponding author: lucia.martvonova@fstroj.uniza.sk

it is more appropriate to choose a design arrangement where the reservoir with the metal hydride will be cooled or heated actively since the intensity of heat transfer directly affects the degree of saturation of the hydride with hydrogen [4]. Therefore, a widespread method of cooling and heating metal hydrides is represented by reservoirs with a pair of holes, where one pair is used for the supply of hydrogen and the other pair ensures the delivery of cooling liquid by convection [5].

2 Construction of a metal hydride storage tank for hydrogen

When storing hydrogen in metal hydride reservoirs, exothermic and endothermic operations occur. For the entire system to be operationally durable, the heat exchange control devices for hydrogen storage must be designed as compact and light as possible with minimal heat loss, also in terms of thermal capacity. It is especially important for the automotive industry, where the reservoirs work in a highly non-stationary mode, which requires a flexible system of heat supply and removal. Cooling and heating systems operating on the principle of heat pipes [6], i.e., with heat transfer based on the phase transformation of the working substance without the need for forced circulation of the working substance using circulating pumps, are shown to be promising devices for the energy management of metal hydride reservoirs. Systems with a thermosyphon effect have several advantages over standard coolers. They do not need a pump to drive the heat-carrying medium, the flow is ensured by the removed heat itself [7]. The heat transfer coefficients are maximum during the phase change, the temperature of the phase transition is stable, and its value can be regulated by pressure or suitable physical properties of the working substance used. To transport heat from and to the reservoir, it is possible to design a thermosyphon heat pipe with a closed loop (Fig.1), which would ensure a homogeneous temperature field in the entire volume of the metal hydride hydrogen reservoir. The use of heat pipes for heat removal or heating is also possible when converting the chemical energy of hydrogen into electrical energy in fuel cells [8], which tend to be the most energetically efficient converters of the accumulated energy in the metal hydride reservoir in the form of hydrogen into electrical energy and when hydrogen is compressed [9].

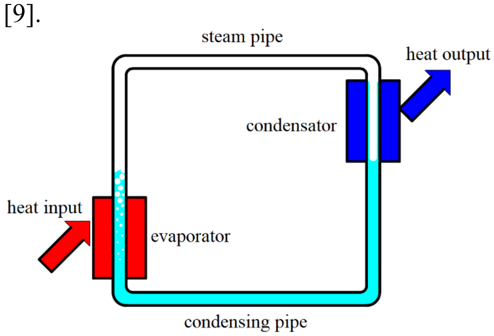


Fig. 1. Loop heat pipe.

The metal hydride storage tank for hydrogen was constructed as a loop heat pipe with an overpressure of about 0.7 MPa (Fig. 2). The metal hydride is stored in the reservoir tubes in the form of pressed briquettes of a cylindrical shape. The tubes are cooled from the side of the outer casing during hydrogen storage by heat removal into the water filling of the space between the tubes while it is heated by natural convection and boiling at a reduced pressure of saturated vapors.

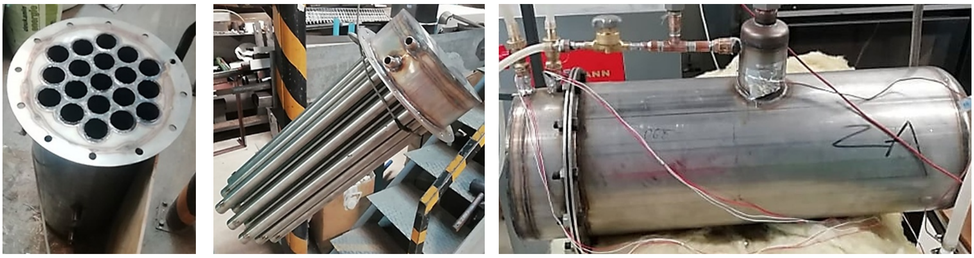


Fig. 2. Realization of a metal hydride hydrogen tank.

3 Mathematical model of metal hydride reservoir cooling using boiling water

Due to the maximum ability to adsorb hydrogen into its structure, the metal hydride filling must be cooled, the recommended cooling temperature is approximately 50 °C. The evaporative part of the closed-loop heat pipe can also be used to cool the metal hydride filling during hydrogen storage. A bundle of tubes closed on one side is in the cylindrical container, which ends with an evaporator, which creates a storage space for the metal hydride (Fig. 3). The space between the tubes is filled with water, which at a lower vapor pressure boils at temperatures significantly lower than the boiling temperature at normal atmospheric pressure.

The heating of the filling due to hydrogen adsorption is simulated by the flow of warm water through a Field tube. Warm water with a temperature of 50 to 70 °C is supplied to the inter-tube space from the thermostat, which is cooled by heat removal into the water-filling space around the bundle of tubes. Under reduced pressure, the steam flows spontaneously into the steam-water heat exchanger, where it condenses and naturally flows back into the space between the tubes. The cooled water returns to the thermostat through the inner pipe. Therefore, in the mathematical model, heat transfer by convection to the outer and inner tubes was solved. Boiling of water at a defined pressure was modeled on the outer surface of the field tube, and heat transfer coefficients on all surfaces, corresponding heat flow densities and corresponding heat outputs were calculated based on the criterion equations.

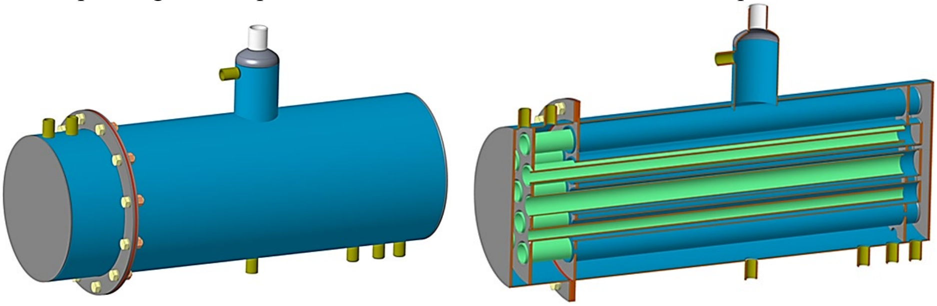


Fig. 3. Model of a metal hydride hydrogen tank.

According to the results from the mathematical model, shown in Figure 4, the heat transfer coefficient by boiling strongly depends on the temperature difference of the wall temperature at which the liquid boils and on the temperature of the water-steam phase transition. The proposed system maintains the temperature of the outer wall of the field tube at 61-64 °C at a pressure of saturated steam of about 20 kPa, and through boiling, heat output of up to 2.5 kW is transferred to the external cooling system.

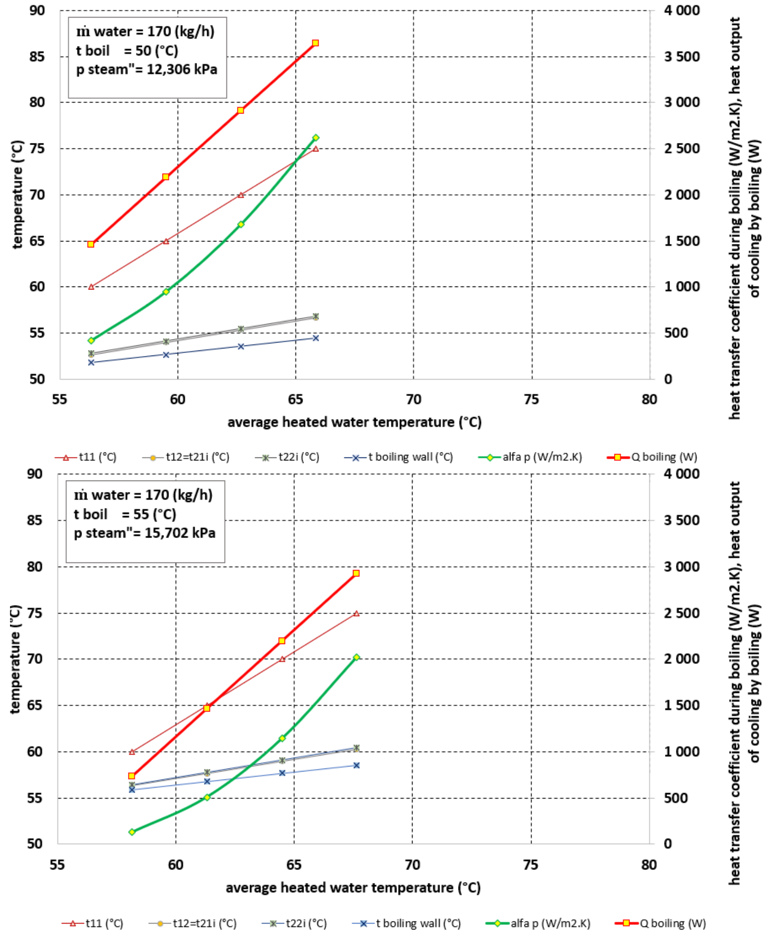
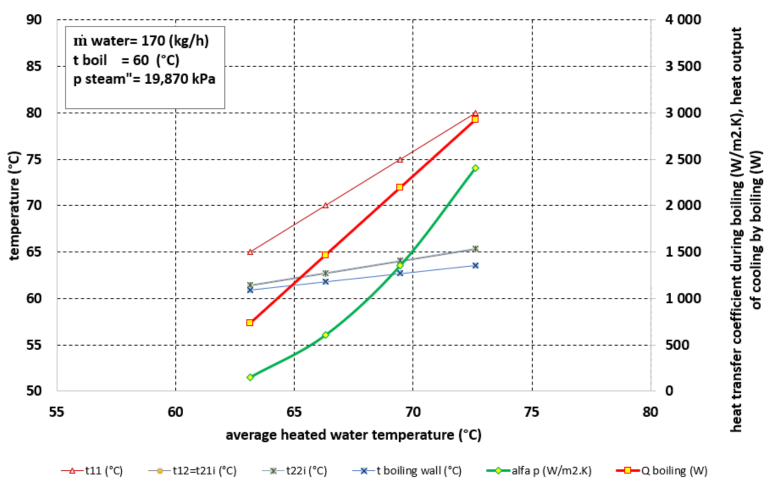


Fig. 4. Dependence of the heat output of boiling water cooling on the mean heating temperature at a pressure in the range of 12.306 – 24.947 kPa (part1).



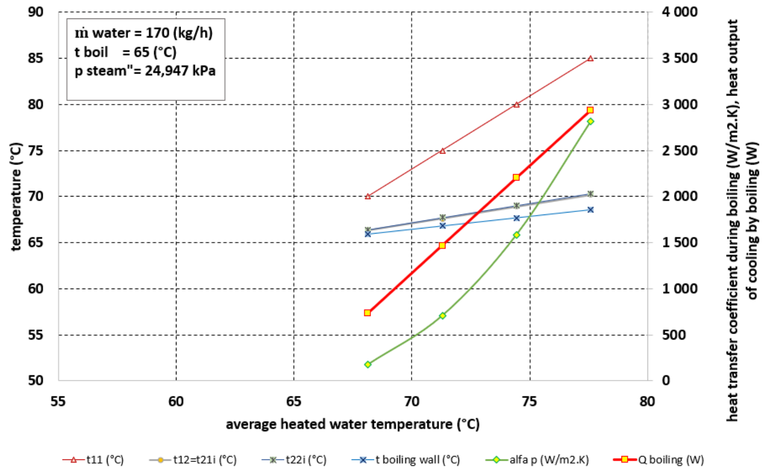


Fig. 4. Dependence of the heat output of boiling water cooling on the mean heating temperature at a pressure in the range of 12.306 – 24.947 kPa (part2).

4 Experimental measurements of thermal performance on a physical model of a metal hydride storage tank for hydrogen

The experimental measurement was carried out on a model of a metal hydride hydrogen storage tank with thermal management using a loop heat pipe (Fig. 5). The cooling mode took place in the form of cooling the tank filling by boiling water at a low pressure of saturated vapors. The reservoir functions as a loop heat pipe evaporator, the condenser of which is a plate steam-water exchanger cooled by water from the water circuit. The steam circuit is realized with a kohaflex metal hose. The heating of the metal hydride filling to the required temperature is simulated by external heating of water in a thermostat with an input of approx. 3 kW.

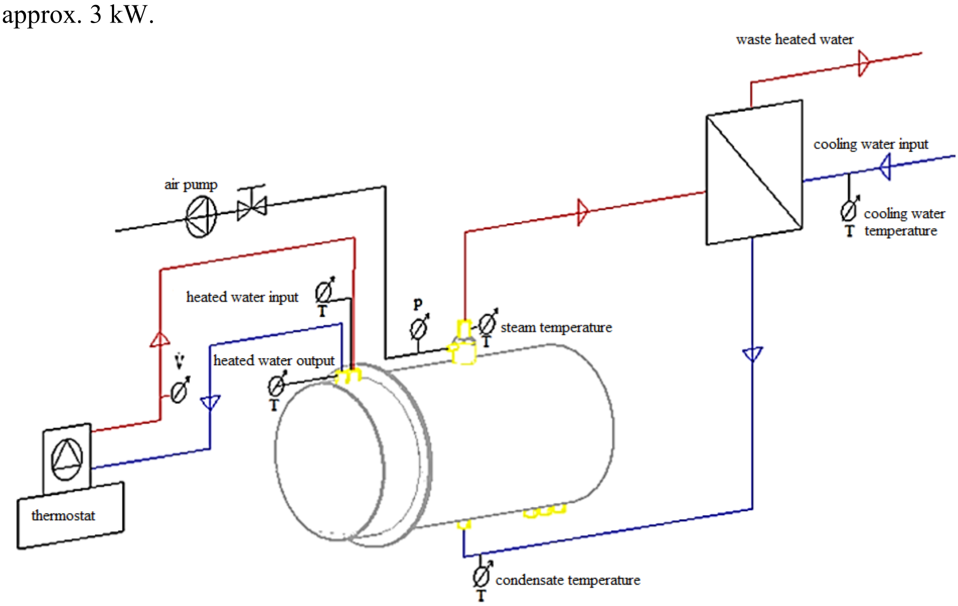


Fig. 5. Experimental measurement scheme.

When refueling with hydrogen from a metal hydride tank, the metal hydride heats up to a temperature of around 50 °C and should not exceed it within an hour. The heating of the metal hydride filling was simulated by the flow of heating water supplied from the thermostat to the space between the tubes. The circulation of heated water between the thermostat and the tank was ensured with the help of the thermostat circulation pump. The flow of heated water was measured by a magnet induction flowmeter, which limited the flow to 176.7 l/h.

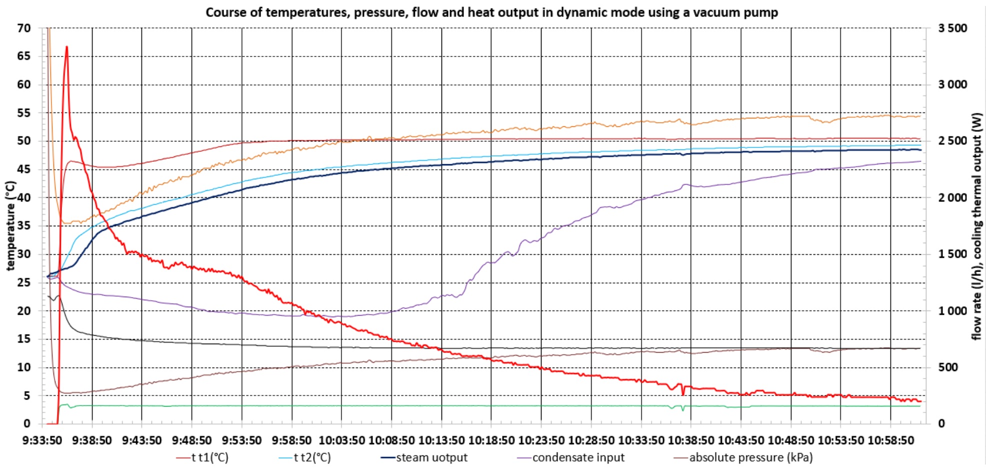


Fig. 6. Course of temperatures, pressure, flow, and heat output in the dynamic model using a vacuum pump.

In fig. 6 shows the course of the measured quantities. For one minute, the system of pipes, packaging, and filling of the reservoir took a peak heat output of up to 3.3 kW. This is due to the thermal capacity of the steel pipes, the steel container, and the water filling of the container, which had a temperature of about 25 °C at the start of the heating simulation. The water filling was heated together with the package, and after heating and intensive boiling, the warmer condensate began to return to the reservoir. The vacuum pump was no longer sufficient to remove the saturated and wet steam, and part of the steam also got into the condenser. Gradually, the boiling stabilized at a power of approx. 250 W and the heating temperatures of the tubes approached the temperature of the exhaust steam. After determining the parameters of the metal hydride alloy, it is possible to simulate the real need for cooling power on the model.

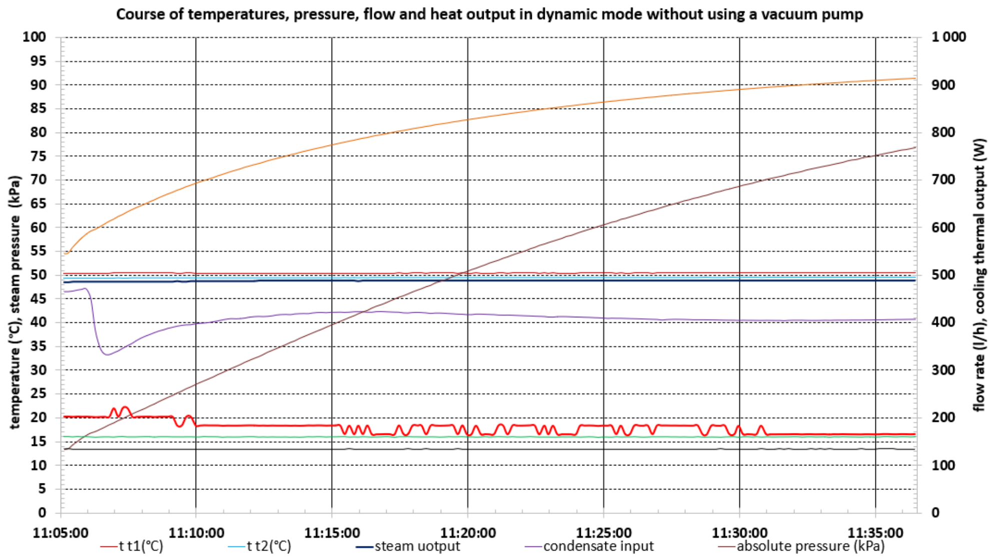


Fig. 7. Course of temperatures, pressure, flow, and heat output in a dynamic mode without using a vacuum pump.

Testing of the cooling system showed that the system is not vacuum-tight and that air, which is one of the non-condensable gases, gets into the reservoir and thus eliminates the processes of intensive heat transport on the wall during phase change.

In fig. 7 shows the course of the quantities without maintaining the pressure using a vacuum pump. The absolute pressure in the reservoir increased with time. As a result of the leak, the pressure increased from 12 kPa to 77 kPa within about 30 minutes, which resulted in an increase in the boiling point of water from 54 °C to 92 °C. The thermosiphon thus switches to Perkins tube mode and the heat output is reduced from approx. 200 W to 170 W.

5 Conclusion

The proposed cooling system has interesting properties from the point of view of heat removal dynamics. When the temperature of the metal hydride suddenly changes from the ambient temperature to a temperature of about 50 °C, the value of the cooling power at the peak is about 3.3 kW. The drop in cooling capacity at a given temperature and pressure is determined by the stable boiling temperature and heating water temperature.

With loop heat pipes, the vacuum tightness of the system is important. Leaks not only increase the pressure but also another component - air, which has diametrically different thermokinetic properties compared to water - gets into the one-component system. Therefore, in the future, it will be necessary to modify the vacuumed part of the system so that it is vacuum-tight. This problem turns out to be critical for achieving high cooling performance values of a water-filled closed-loop heat pipe system.

The experiments also confirmed that the designed simulator can test heating at different inlet temperatures and flow rates. In our case, we were limited by the maximum flow through the magnet induction flowmeter, which was about 170 l/h. In the case of a higher flow rate, more uniform heating of the outer tube would be achieved, which would correspond more closely to the real situation.

When approaching the real conditions in which heat is released from the volume of the alloy, it will be necessary to realize the heating of a similar significantly cheaper filling with the thermokinetic properties of the metal hydride alloy, apparently electrically as Joule heat.

Based on the measurement of electrical quantities, the determination of the released heat, which must be removed by the cooling system, would be significantly more accurate. Such a method of measurement would allow the measurement of surface temperatures on the surface of the metal hydride filling or even in its center. This information would make it possible to predict the accumulation dependence of the alloy more accurately on its temperature.

This work was supported by the Grant System of the University of Zilina No. 1/2021 (15898) "Verification of the principle of thermal management of a metal hydride (MH) hydrogen storage tank using a loop heat pipe", KEGA 046ŽU-4/2021 "Innovative methods of increasing the thermal efficiency of small heat sources using heat recovery through phase transformations" and KEGA 047ŽU-4/2022 "Innovative approaches to fluid dynamics modeling in energy systems".

References

1. Jinsong Zhang, Timothy S. Fisher, P. Veeraraghavan Ramachandran, Jay P. Gore: A Review of Heat Transfer Issues in Hydrogen Storage Technologies, Journal of Heat Transfer 127(12), 2005.
2. M.W.Davids et al: Metal hydride hydrogen storage tank for light fuel cell vehicle. International Journal of Hydrogen Energy, Volume 44, 2019.
3. Mykhaylo Lototskyy et al: Metal hydride hydrogen storage tank for fuel cell utility vehicles. International Journal of Hydrogen Energy, Volume 45, Issue 14, 2020.
4. S.Mellouli et al: Integration of thermal energy storage unit in a metal hydride hydrogen storage tank. Applied Thermal Engineering, Volume 102, 2016.
5. MahvashAfzal et al: Heat transfer techniques in metal hydride hydrogen storage: A review. International Journal of Hydrogen Energy, Volume 42, 2017.
6. Yuzhu Liu, Hui Wang, Ajay Prasad, Suresh G. Advani: Role of heat pipes in improving the hydrogen charging rate in a metal hydride storage tank. International Journal of Hydrogen Energy 39(20): 10552–10563 DOI:10.1016/j.ijhydene.2014.04.197
7. Gavlas, S., Jandačka, J., Malcho, M.: Zariadenie na samočinný prenos tepla so samoregulovateľnou nastaviteľnou teplotou vody. Úžitkový vzor č. SK 7672 Y1, Úrad priemyselného vlastníctva Slovenskej republiky 2016.
8. Anggito P. Tetuko, Bahman Shabani, and John Andrews: Passive Fuel Cell Heat Recovery Using Heat Pipes to Enhance Metal Hydride Canisters Hydrogen Discharge Rate: An Experimental Simulation. Energies 2018.
9. Robert C. Bowman Jr.: Metal Hydride Compressors with Gas-Gap Heat Switches: Concept, Development, Testing, and Space Flight Operation for the Planck Sorption Cryocoolers. Inorganics (ISSN 2304-6740; CODEN: INORCW) 2019.