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Open Sorption Cooling System Based on Metal Hydrides

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1 Introduction

Onboard hydrogen storage is one key issue for efficient hydrogen fuelled cars. Besides the chemical storing method in e.g. metal hydrides, two physical techniques, liquefaction and compression, are mainly used to increase the energy density of hydrogen storage tanks. Due to the low specific storage capacity of available metal hydrides, the physical storing techniques - especially the compression of hydrogen - seem currently more promising. However, the energy consumption due to the compression of hydrogen is around 15.5 % (800 bar) of its lower heating value and reduces the overall energy efficiency of the car [1].

Therefore, this work focuses on the utilization of the potential energy of the hydrogen storage tank that is available onboard. Based on conventional metal hydride sorption systems, an open sorption system is proposed that is able to utilize this energy to generate a cooling effect usable for e.g. air-conditioning.

2 Background and Working Principle of the Open Sorption System

In Figure 1 idealized van't Hoff diagrams of metal hydride based sorption cooling systems are shown. In both cases, the cooling effect is generated during the cooling half-cycle by the endothermic desorption of hydrogen of metal hydride A at the low pressure p_{Cool}. As the amount of hydrogen stored in metal hydride A is limited, it has to be recharged at the higher pressure level p_{Reg} during the subsequent regeneration half-cycle. The respective pressures (p_{Cool} and p_{Reg}) depend on the van'f Hoff characteristic of the applied metal hydride A and on the temperature boundary conditions.

The underlying principle of the closed sorption cooling system (left) is the coupling of an adapted second metal hydride (B) that operates as a thermally driven compressor between both pressure levels. Therefore, hydrogen is used as working fluid that is cycled between both metal hydrides but not consumed. Several closed metal hydride sorption systems have been realized within the last years with different metal hydrides as well as various metal hydride reaction bed designs. In order to reduce the half-cycle time of the respective system, different measures to increase the heat transfer within the powder bulk, like metal foams [2, 3] or metal hydride pellets [4, 5], have been intensively investigated. Very recently, a review article has been published that summarizes the practical state of the art of closed metal hydride sorption systems [6].

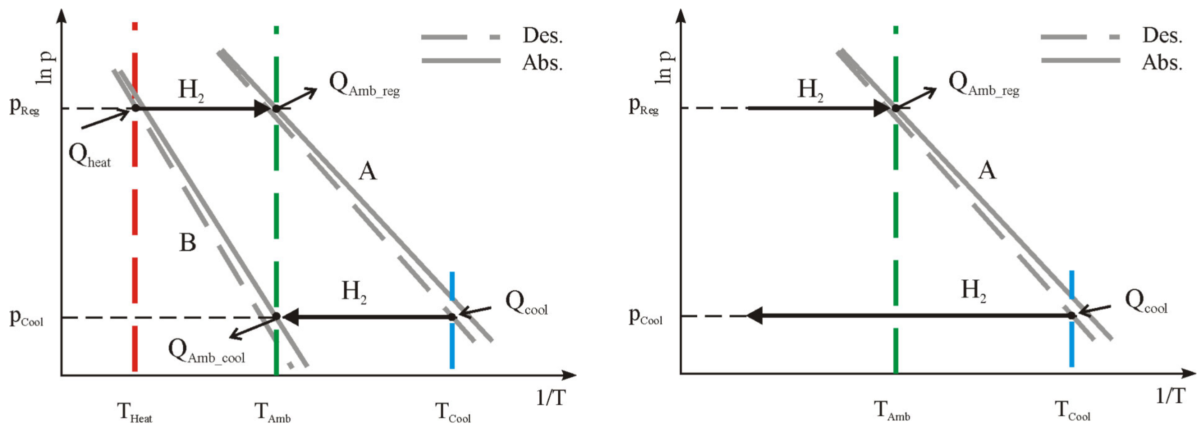

Figure 1: Van't Hoff diagrams of the closed (left) and the open (right) sorption cooling system.

Contrary to the closed metal hydride sorption system, the proposed new system operates with one single metal hydride (A). It is an open process which demands a hydrogen source at a high pressure level (p_{Reg}) and a hydrogen consumer at a low pressure level (p_{Cool}). If hydrogen is stored onboard in compressed state, both boundary conditions are available (hydrogen storage tank and fuel cell) and the open sorption system can be integrated and utilize the pressure difference. This system is schematically shown in Figure 2. In order to reach quasi-continuous cold output, it consists of two reactors that are connected to the fuel cell (FC) and to the hydrogen storage tank (PH_2). Two water cycles (pump, heat exchanger, two 3-way valves) are necessary to remove/supply the thermal energy of the reaction.

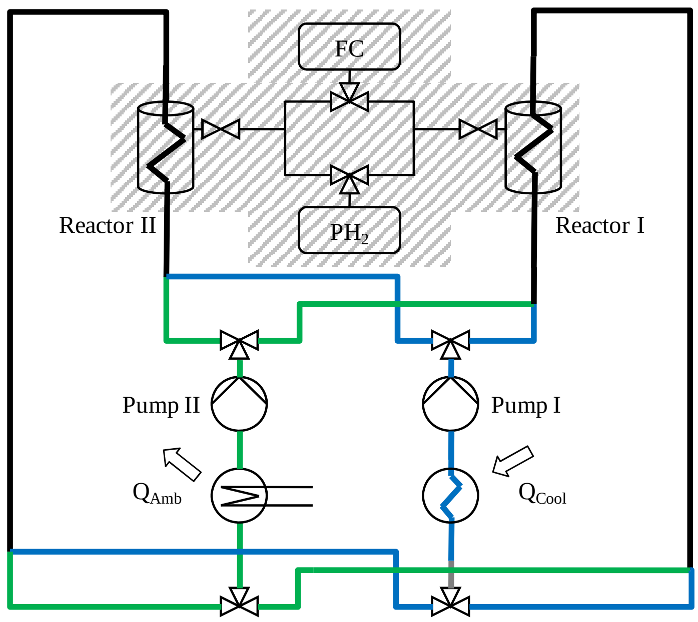

Figure 2: Schematic principle of the pressure-driven sorption system including all major secondary components.

The cooling effect is generated by the reactor that is connected to the hydrogen consumer (e.g. fuel cell) and desorbs hydrogen at the pressure p_{Cool}. The necessary heat of reaction (endothermic desorption) has to be supplied by the blue water cycle that operates at the cooling temperature (T_{Cool}). At the same time, the second reactor is regenerated with hydrogen (at p_{Reg}) from the storage tank and the generated heat of absorption is transferred to the ambient by means of the green water cycle.

Therefore, the metal hydride characteristic has to be adapted to the supply pressure of the hydrogen consumer and to the required cooling temperature. The necessary regeneration pressure for the sorption system is then defined by the ambient temperature.

3 Test Bench and Applied Metal Hydride Reaction Bed

The test bench used for experimental investigations of one reactor of the open sorption system is shown in Figure 3. It consists of a hydrogen part (thin lines) and a water cycle to supply/remove the thermal energy of the chemical reaction (thick lines). As the hydrogen part is separated by valve V7 into two areas, area 1 can be separately prepared for the respective experiment. In case of an absorption experiment, the hydrogen volumes are filled with hydrogen (p_{Reg}) and as soon as valve V7 is opened, the chemical reaction is monitored by several temperature (T1-T4) and pressure sensors (p1, p2). In order to keep the pressure change in the closed system reasonably small, hydrogen bottles with a total volume of around 52 l are used.

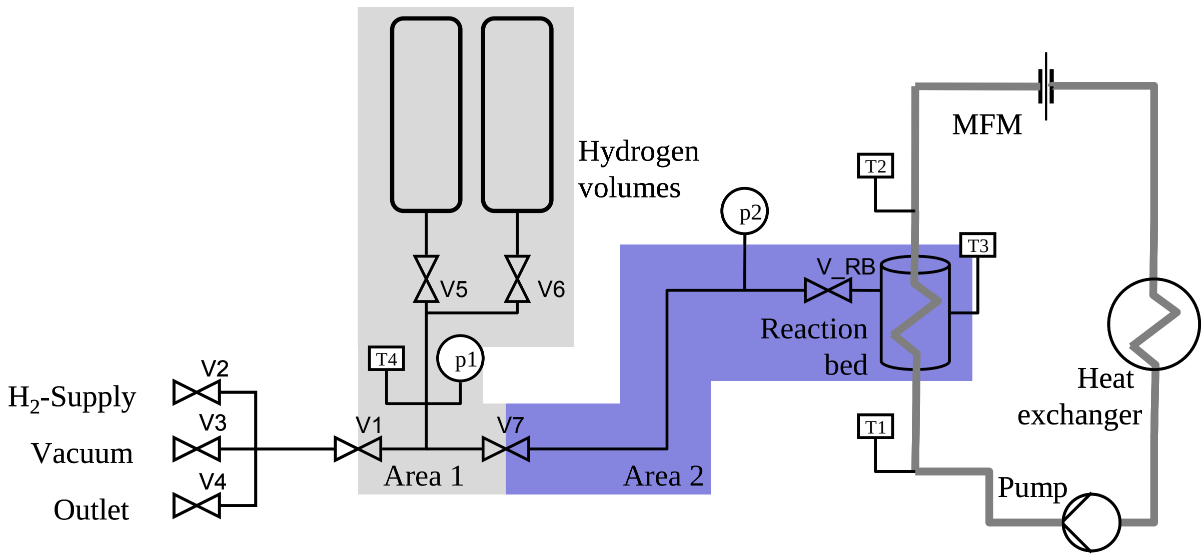

Figure 3: Schematic diagram of test bench.

In Figure 4 the applied reaction bed is shown. It consists of a capillary tube bundle heat exchanger (left) that is surrounded by a sintered metal filter tube (middle). The heat transfer fluid flows through the 372 capillary tubes (inner diameter of 1.4 mm) and the metal hydride powder is located in the outer part of the tube bundle. Hydrogen is distributed around the filter tube through an annular gap that is formed by the cladding tube of the reactor (right).

Figure 4: The capillary tube bundle reaction bed.

The total length of the assembled reaction bed is 135 mm. With an outer diameter of 76 mm the total volume of the reaction bed is around 0.6 l. Its weight without metal powder is around 1.7 kg. The volume within the sintered metal tube ($V_i \approx 0.23$ l) is sufficient to charge 800-1000 g of powder, depending on the density of the alloy.

4 Preliminary Experimental Results

Based on PCI measurements of different metal hydrides, $T_{0.99}Zr_{0.01}V_{0.43}Fe_{0.09}Cr_{0.05}Mn_{1.5}$ was chosen for first experimental investigations with one reactor of the open sorption system. The measurement results were obtained with the capillary tube bundle reaction bed and a metal hydride mass of 800 g. The measured cooling and regeneration half-cycles are shown in Figure 5 and Figure 6, respectively.

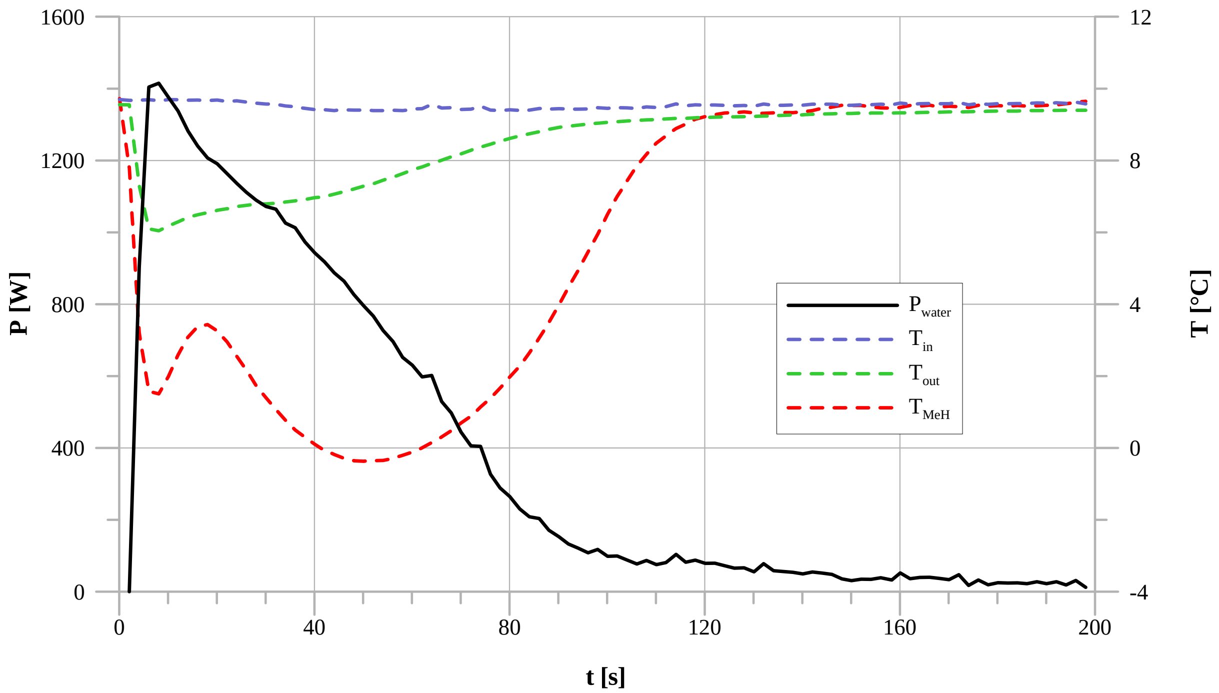

Figure 5: Measured cooling half-cycle for T_{in} = 10 °C with $p_{H2} \approx 5$ bar.

The thermal power P_{water} corresponding to the left y-axis is drawn as solid line and the respective temperatures (right y-axis) are drawn with dashed lines. The desorption pressure during the cooling half-cycle experiment (Figure 5) was set to 5 bar. With an inlet temperature of around 10 °C, a peak cooling power of around 1,400 W is achieved. The average cooling power is 800 W and the necessary half-cycle time is around 100 s.

The system pressure during the regeneration half-cycle (absorption, see Figure 6) was adjusted to 50 bar. For an inlet temperature of 35 °C, the time necessary to charge the metal hydride completely is comparable to the time of the desorption process (~ 100 s). Due to the very fast reaction at the beginning of the experiment, the maximum thermal power during regeneration is about 2,700 W.

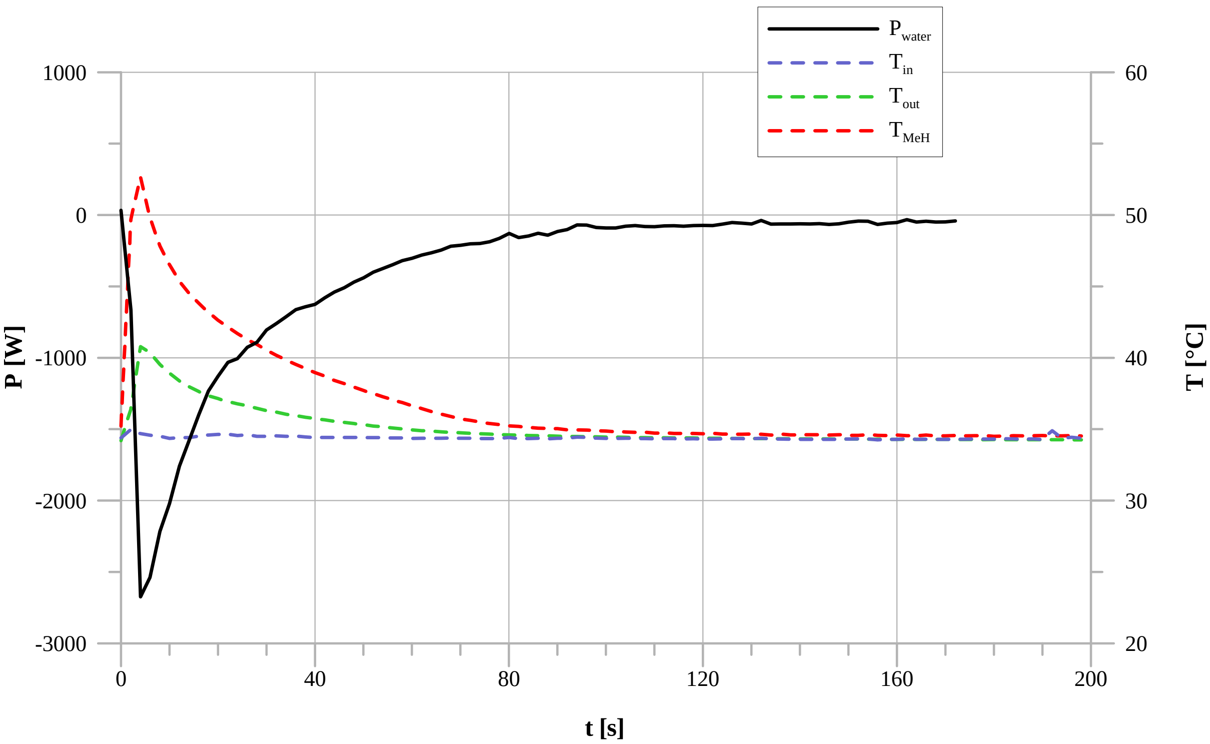

Figure 6: Measured regeneration half-cycle for T_{in} = 35 °C and p_{H2} ≈ 50 bar.

Both experiments show the possibility to operate an open sorption system between 5 bar and 50 bar hydrogen pressure. The achievable cooling temperature is below 10 °C and the regeneration at 35 °C (ambient temperature) is demonstrated in Figure 6. As the temperature and pressure boundary conditions of the cooling system depend on the implemented alloy, the system principle can be adapted to the hydrogen consuming unit, e.g. fuel cell by modifying the alloy composition.

Weight and volume constraints

Due to the simple system set-up consisting of only two reaction beds, the complete system can be very compact and lightweight. The weight of the reaction bed used for the described experiments is around 2.5 kg, including 800 g of metal hydride. A linear up-scaling to an average cooling power of 2 kW leads to a total weight of the hydrogen part of around 12.5 kg (two reaction beds for continuous cold output). The volume of this part can be estimated to around 3 l (not including the hydrogen valve and connections).

Necessary hydrogen flow rate

Due to the coupling of the open sorption system to a hydrogen consuming unit (e.g. fuel cell), the cooling effect is only generated as long as hydrogen is consumed. Therefore, the generated cooling power of the open sorption system depends directly on the consumed hydrogen flow rate. This dependency is comparable to conventional air-conditioning systems that are mechanically coupled to the engine. Based on the desorption enthalpy of the applied metal hydride (22.6 kJ/mol) and neglecting the losses due to the heat capacity of the reactor (operation temperatures between T_{Amb} and T_{Cool}), the necessary hydrogen flow rate is around 0.09 mol/s if a cooling power of 2 kW is required. If more hydrogen is consumed by the fuel cell than desorbed by the metal hydride, a bypass solution could ensure the necessary hydrogen supply rate.

5 Conclusions and Outlook

In this work an open sorption system based on metal hydrides is described. According to preliminary experimental results with one reaction bed using 800 g of $T_{0.99}Zr_{0.01}V_{0.43}Fe_{0.09}Cr_{0.05}Mn_{1.5}$ the system is able to generate a cooling effect at a temperature below 10 °C with a desorption pressure of 5 bar and can be regenerated at 35 °C with an absorption pressure of 50 bar. However, more detailed experimental investigations are necessary and will be performed on the test bench of the complete system that is currently under construction at the Institute of Nuclear Energy and Energy Systems (IKE).

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