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Experimental results of a compact thermally driven cooling system based on metal hydrides

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ABSTRACT

In this paper a detailed experimental analysis of a metal hydride based cooling system is presented. For the high temperature side an AB_5 type alloy ($LmNi_{4.91}Sn_{0.15}$) was chosen, whereas an AB_2 type alloy ($Ti_{0.99}Zr_{0.01}V_{0.43}Fe_{0.09}Cr_{0.05}Mn_{1.5}$) is used for the low temperature side. Due to very good heat and also mass transfer characteristics (among others, large heat transfer surface area) of the utilized capillary tube bundle reaction bed, very short half-cycle times in the order of 100 s have been reached. Consequently, the specific cooling power of the system is up to 780 W per kg desorbing metal hydride – depending on the temperature boundary conditions. The system was experimentally analyzed for different cooling and ambient temperatures, whereas the heating temperature was fixed to 130 °C.

1. Introduction

The thermally driven generation of cold seems to be a reasonable way to utilize waste heat to increase the overall efficiency of energy conversion systems. In case of automotive cooling, a thermally driven cooling system could supply the cooling demand using waste heat from the coolant or the exhaust gases. The substitution of mechanical energy (generated by the engine) by waste heat as main driving energy for the cooling system would consequently lead to reduced fuel consumption along with reduced CO_2 emissions. Additionally, the climate damaging refrigerants of current automotive air-conditioning systems could be replaced. However, main obstacles for an automotive application of thermally driven sorption systems are their current weight and volume constraints.

Due to the fast intrinsic reaction kinetics of metal hydrides, compact and light-weight sorption systems can be realized if limitations due to insufficient mass or heat transfer within the reaction bed can be minimized. Therefore, this work focuses on the experimental investigation of a metal hydride sorption system using capillary tube bundle based reaction beds in order to increase the weight specific power of the system.

1.1. *Working principle*

The basic configuration of metal hydride sorption systems consists of two reaction beds coupled by a hydrogen connection pipe. Each reaction bed contains a different metal hydride, indicated as A and B (Fig. 1). As the equilibrium pressure of metal hydride A is higher than the equilibrium pressure of metal hydride B at the same temperature, metal hydride A tends to release hydrogen and cools down. If the coupled metal hydride B is able to absorb the released hydrogen, a hydrogen exchange along with the corresponding cooling effect is obtained (cooling half-cycle). The absorption of hydrogen in the coupled low-pressure hydride B generates heat (Q_{Amb_cool}) that must be released to a heat sink to prevent

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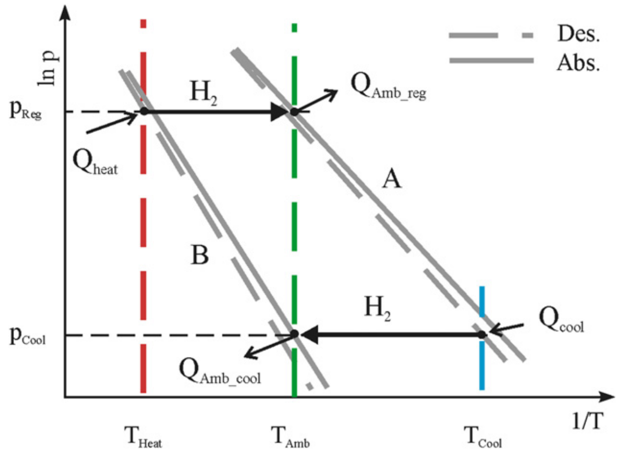

Fig. 1 – Van't Hoff diagram of sorption cooling system.

a temperature increase of the alloy. As the environment is generally used as heat sink its temperature (T_{Amb}) determines the characteristic of the coupled alloy B.

As soon as the maximum amount of hydrogen is exchanged, the flow direction must be reversed. Therefore, a thermal energy input (Q_{Heat}) is necessary to supply the desorption enthalpy of metal hydride B. As the absorption heat during regeneration (Q_{Amb_reg}) is released to the environment, the absorption pressure of metal hydride A at ambient temperature determines the necessary regeneration pressure level (p_{Reg}).

The described batch system is not able to supply a continuous cooling effect. As the reaction bed pairs working either in regeneration or cooling mode, two identical reaction bed couples working in opposite direction are necessary to realize a quasi-continuous cold output. Therefore, the necessary time for regeneration must be shorter or at least identical to the cooling half-cycle time.

1.2. *State of the art*

In order to compare different designs of metal hydride sorption systems regarding their weight specific performance, two characteristic values can be deduced from published data, the specific power (per kg desorbing alloy in the respective reaction bed) and the half-cycle time. Although the systems may be designed for different applications, like combined heat/cold generation or heat transforming, for each system the same principle applies: thermally driven hydrogen exchange between two reaction beds. The limiting factors (quantified by specific power and half-cycle time) are therefore independent of the designed application, the total number of reaction beds or the amount of different metal hydrides.

In general, metal hydride reaction beds for sorption systems are of cylindrical shape with two different possible hydrogen distribution designs: Hydrogen enters the metal hydride bulk either through an inner filter artery or through a surrounding filter tube. Both cases enable an easy hydrogen distribution along the axial direction, whereas the radial hydrogen distribution characteristic depends on the consistency of the bulk material. The reaction bed design with an inner artery was intensively used to investigate different sorption system prototypes [1–5]. The second design for hydrogen distribution was recently investigated by Qin et al. [6] and Ni et al. [7] in 2007. Instead of a central filter tube, the filter surrounds the metal powder bulk. Therefore, hydrogen enters the reaction bed from one side, is distributed in the annular gap around the filter and enters in radial direction into the powder bulk. A finned copper tube is inserted in the bulk to divide the bed into several sections and to improve the heat transfer characteristics. Kang et al. [8] used a comparable design: The reaction bed consisted of two identical copper tubes with aluminum fins working serially in an U-shaped heat exchanger and hydrogen distribution was realized by a gap between the metal hydride part of the reaction bed and its pressure vessel.

Although, heat recovery measures of the systems and different working temperatures complicate a direct comparison of the systems, the relevant weight-specific characteristics for coupled metal hydride reaction beds realized within the last 15 years can be summarized as follows:

- The half-cycle time ranges between 10 and 20 min, depending on the applied reaction bed design.
- The maximum achieved specific power is around 140–170 W per kg desorbing alloy of the respective reaction bed.

As most of the intended applications were stationary, the necessity to increase the specific power by means of heat transfer enhancements was mainly based on the reduction of metal powder and not implicitly on weight and volume optimizations. However, taking into account weight and volume constraints of automotive applications, the need to increase the weight specific performance of the metal hydride sorption technology is obvious. Therefore, this work focuses on the experimental analysis of a sorption system using a capillary tube bundle based reaction bed with a large heat transfer surface.

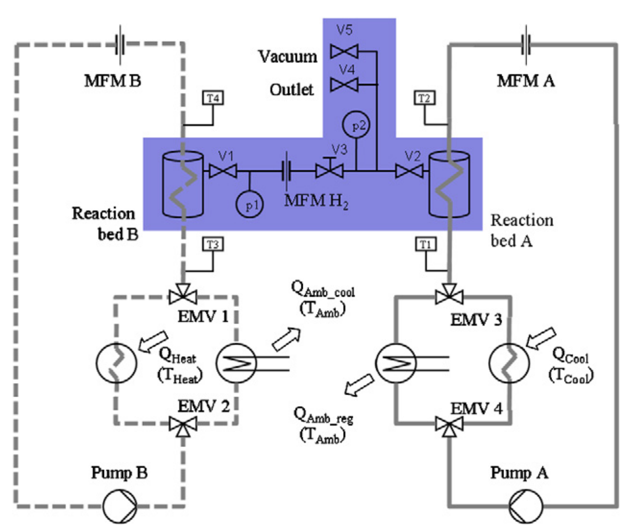

Fig. 2 – Schematic flow diagram of test bench for coupled reaction beds.