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# A/C-APU – Innovative Air Conditioning Unit Based on Hydrogen to Extend the Driving Range of EVs and FCEVs

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**Summary**

In this work, an innovative vehicle air-conditioning unit that provides heat, cold and electric power is presesented. The environmentally friendly unit is based on the integration of two alternately working compact metal hydride reactors between a hydrogen pressure tank and a fuel cell. At the component-level the design and testing of two small lab-scale reactors is explained. At the vehicle-level it is shown that it is possible with this hydrogen-based unit to reutilise up to 75% of the compression work in the tank to increase the range of fuel cell cars by up to 8% in hot weather conditions.

*Keywords: air conditioning, electric vehicle, fuel cell, hydrogen, metal hydride*

## 1 Introduction

For cabin air-conditioning in electric vehicles using batteries or fuel cells and also for temperature equalization of the powertrain, mainly electrical systems are used. For example, an air compressor is implemented for cooling in summer and an electrical heater is used for heating in winter. These components have huge energy requirements at the expense of the final driving range which is reduced by up to 43% in hot weather conditions [1]. Since the range is one of the main criteria for customer acceptance, the usage of a hydrogen based thermal system for heating and cooling might be a promising alternative. Especially as such a hydrogen system does not require any greenhouse gas emitting refrigerant, which is environmentally advantageous.

The combination of such a thermal system with a fuel cell is the so-called air-conditioning and auxiliary power unit (A/C-APU), which can be used as an auxiliary power unit with the ability to provide cold for battery electric vehicles and fully integrated in a fuel cell driven electric vehicle (FCEV). Thus, with the A/C-APU an increase of vehicle range can be achieved.

The structure of the paper is as follows. First, the A/C-APU and the working principle of the air-conditioning based on hydrogen and metal hydrides is described in detail. Then, the realized novel reactor design, two test benches to evaluate the A/C-APU system as well as first experimental results are illustrated. The paper concludes with the evaluation of the A/C-APU technology in a fuel cell vehicle using an overall vehicle simulation model.

## 2 Working principle of the A/C-APU

Apart from the storage of hydrogen, metal hydrides (MeH) can be used for the vehicle air-conditioning when the exothermal or endothermal character of the reaction is used. In this approach, the characteristic of the endothermic desorption of hydrogen in MeH is applied to generate a cooling effect. On material basis, MeH enable both very high reaction rates and reaction enthalpies. Thus, only low MeH masses are required and small systems can be realized.

According to Fig.1, for a continuous cooling effect two identical and compact metal hydride reactors have to be integrated between the pressure tank and the fuel cell. In two half-cycles, these reactors are alternately charged and discharged with hydrogen. In the so-called regeneration half-cycle, a metal hydride reactor (in this example MeH 1) is charged with hydrogen from the hydrogen pressure tank. Since the absorption is an exothermic reaction, heat has to be released to the ambient. In the following cooling half-cycle, the hydrogen is subsequently released to the fuel cell by absorbing heat at a low temperature level and thus cold is generated (endothermic reaction). A second metal hydride ractor (in this example MeH 2) alternately passes the same two half-cycles for a continuous cooling effect.

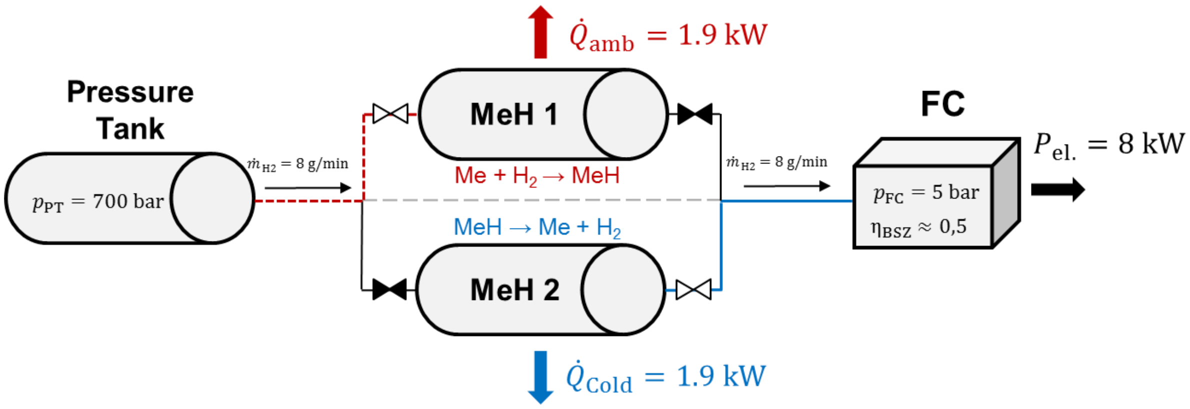



Figure 1: Working principle of a cooling and heating system based on metal hydrides

The driving force of the system is the on-board existing pressure difference between the pressure tank ($p_{\mathrm{DT}} \approx 700$ bar) and the fuel cell ($p_{\mathrm{FC}} \approx 5$ bar). In state of the art vehicles, during operation the hydrogen pressure is throttled down to the fuel cell level. Thus, the compression work that has to be applied at the hydrogen filling station is so far wasted. This lost energy amounts to approximately 5 kWh $\mathrm{kg}^{-1}_{\mathrm{H2}}$ and corresponds to 15% of the the lower heating value of hydrogen. In [2], it is shown that it is possible with such a system (also known as open cooling system or MeH cooling and heating system) to reutilise up to 74% of this compression work. Therfore, the on-booard available pressure difference is used to generate cold and heat at the same time and hydrogen is not consumed.

The average cooling power of the system is depending on the hydrogen consumption of the fuel cell. For instance, for an electric power of $P_{\mathrm{FC}} = 8$ kW and a hydrogen mass flow of $8\,\mathrm{g} \cdot \mathrm{min}^{-1}$, a theoretical cooling power of $\dot{Q}_{cold} = 1.9$ kW can be generated. This value corresponds to a ratio $\dot{Q}_{cold} \cdot P_{\mathrm{FC}}{}^{-1}$ of 24%. Sensible losses that occur in continuous operation reduce this value. Thus, the design of the reactor (see section 3.1) decides whether this theoretical ratio of 24% is obtainable when it comes to a technical implementation of the system.

For a sufficient cooling effect and a functionality of the system, the thermodynamic properties of the selected MeH should fit to the requierements that are given for the vehicle integration. First of all, for an absorption pressure $p_{\mathrm{abs}}$, the equilibrium temperature of the material should be above 50 °C, since a temperature gradient is necessary to release the heat of the reaction to the ambient. For reasons of functionality, hereby the absorption pressure is fixed to $p_{\mathrm{abs}} = 30 - 40$ bar as for this pressure level the hydrogen pressure tanks is considered as empty.

For a sufficient cooling effect at a fuel cell pressure of $p_{\mathrm{FC}} = 5$ bar, the equilibrium temperature of the material should be around $T_{\mathrm{cold}} = 0 - 5$ °C. These equilibrium requierements can be schematically summarised in the characteristic Van´t Hoff plot in Fig.2. In this plot, the hydrogen equilibrium pressure is shown as function of the reciprocal metal hydride temperature. Additionally, for a compact system, the metal hydride has to permit very short half-cycle times in the range of 1 min and should offer a high cycling stability for more than 10.000 cycles. Taking into account these requierements, the metal hydride C1 ($Ti_{0.99}Zr_{0.01}V_{0.43}Fe_{0.09}Cr_{0.05}Mn_{1.5}$) is a suitable material for the application in the MeH cooling and heating system. For a fuel cell inlet pressure of 5 bar the equilibrium temperature of the metal hydride C1 is $T_{\mathrm{cold}} = -5$ °C. In the regeneration half-cycle, for $p_{\mathrm{abs}} = 40$ bar a metal hydride temperature of $T_{\mathrm{amb}} = 50$ °C is obtainable [2].

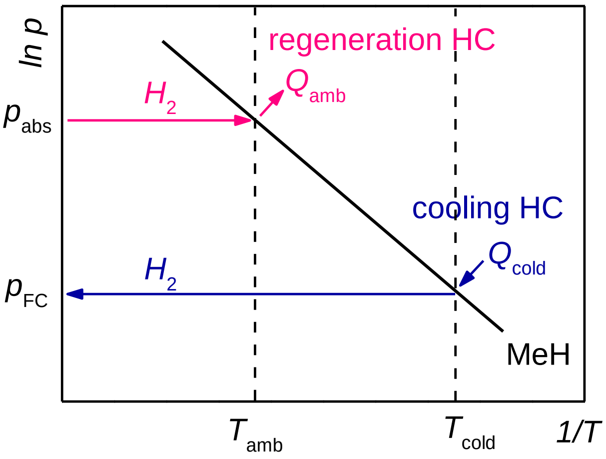



Figure 2: MeH selection criteria according to the Van´t Hoff plot.

The A/C-APU is the unit that combines the MeH cooling and heating system with the fuel cell and the hydrogen pressure tank. To offer an optimal solution for battery electric vehicles as well as fuel cell vehicles, a modular concept for the A/C-APU has been designed at the DLR. The fuel cell converts the chemical energy in hydrogen into electrical energy and heat that enables both an increase of vehicle range and heating in winter months. Additionally, cold is generated for the passenger compartement and powertrain components by the integrated MeH cooling and heating system explained above. Thus, a combined system for vehicle thermal management and range extension is obtained.

With a standard high-voltage interface, the A/C-APU can be integrated into the high-voltage system of any electric vehicle in order to use the generated electricity for the drive. The generated heat and cold is distributed via a cooling medium. This is realized by combining the two subsystems (fuel cell and MeH system) with a coolant circulation system consisting of coolant pumps and valves. The A/C-APU operates in a temperature range from -15 °C to 60 °C. Using a standard water interface, the unit can be integrated into any vehicle's cooling system and can match the temperature of the vehicle’s battery as well as the air conditioning of the cabin. In a heating mode, the waste heat of the fuel cell and reactors can be provided to warm the cabin and the battery at cold temperatures. In a cooling mode, the cold generated by the MeH reactors can be used to cool both the cabin and the battery pack.

## 3 Reactor design and test benches

In this section, based on design of the A/C-APU unit a novel plate reactor for the MeH cooling and heating system is described. Additionally, a realized test bench for two alternately working MeH reactors as well as the complete AC/APU setup including a 8 $kW_{el}$ polymer electrolyte membrane (PEM) fuel cell is presented.

## 3.1 Design of the reactors

In order to realise a compact and lightweigtht system, the design of the reactors has to fulfil certain criteria that are discussed and described in detail in [3]. In particular, the following two aspects have to be considered when an efficient reactor design has to be attained:

As a result of the low thermal conductivity of the metal hydride (in the the range of $1 \div 1.5\ \mathrm{W\,m^{-1}\,K^{-1}}$) short heat transfer paths from the metal hydride have to be enabled to avoid heat transfer limitations. Thus, due to short reaction times a high specific cooling power can be gained. Secondly, based on the temperature change between regeneration ($T_{\mathrm{amb}}$) and cooling half-cycle ($T_{\mathrm{Cold}}$) in the continuous operation, a part of the thermal power of the reaction is lost. As a result and in simultaneous consideration of the mechanical stability of the reactor the mass should be reduced to the minimum.

In this approach, a plate reactor based on a soldered plate heat exchanger from VAU Thermotech GmbH & Co. KG[1] is used (cf. Fig. 3). Hereby, the metal hydride and the heat transfer fluid (HTF) are alternately arranged in a very small gap width of around 1.5 mm. On the heat transfer fluid side, stamped plates enable a high heat transfer coefficent from the reactor wall to the fluid. As a result of the high overall heat transfer coefficient, short reaction times and high specific cooling powers are obtainable. On the metal hydride side of the reactor, an integrated sinter metal filter (mesh $3 \times 10^{-3}\mathrm{mm}$) enables an uniform hydrogen transport to each plate and prevents material leaking. A further advantage of the plate reactor design is its scalability. By increasing the number of plates – heat and and mass transfer remain unaffected – the design can be adapted to applications with a higher demand of cooling power. In a first approach, only small lab-scale plate reactors with a metal hydride mass of around 350 g and a reactor volume of 0.75 l are applied for the single reactor measurement and the proof of concept of the MeH cooling and heating system, respectively (cf. section 4).

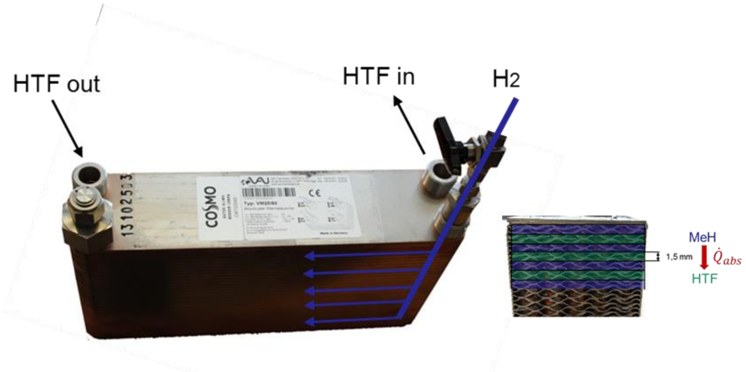



Figure 3: Design of the soldered plate reactor.

## 3.2 Description of the test benches

Based on the defined reactor design, a test bench is built that enables a continuous and alternating charging/ discharging of the two plate reactors. In a next step, to proof the concept of the A/C-APU the test bench of the reactors is going to be coupled with a 8 kW PEM fuel cell test bench that is described in this section.

In principle, the test bench for the alternately working MeH reactors consists of a hydrogen part with a valve system (upper level) that permits an independentant distribution of hydrogen from (desorption) or to (absorption) the reactors. Additionally, two heat transfer fluid cycles with an adjustable tempering unit and a second valve system (lower level) simulate the temperature levels of both regeneration and cooling states. For the continuous operation of the system, a fixed time or minimum transferred cooling power criterion is implemented in the control unit of the test bench that automatically switches between the two states by controlling the valve systems.

Thus, the test bench allows to evaluate a continuous working system with two reactors as a function of the boundary conditions ($T_{\mathrm{cold}}$, $T_{\mathrm{amb}}$ and $\dot{V}_{\mathrm{HTF}}$) and in consideration of sensible reactor and fluid losses. The

[1] https://www.vau-thermotech.de/mediapool/40/409506/data/Technische_Datenbl_tter_VM25.pdf

thermal power of the system is determined by measuring the temperature difference between the reactor in- and outlet as well as the HTF flow rate. A photograph of the experimental setup next to the functional scheme is shown in Fig. 4 [4].

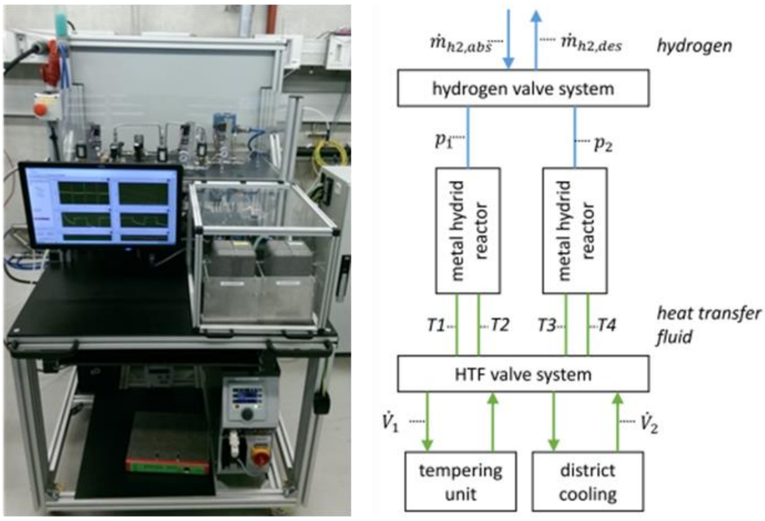



Figure 4: Test bench for the alternately working MeH reactors [4]

The test bench for the fuel cell consists of a fuel cell as main component, a DC electronic load, a cooling circuit and a hydrogen source. In addition to these components, the test bench is equipped with several different sensors in order to measure necessary physical quantities of the fuel cell system. For example, to monitor different states of the coolant, temperature and flow sensors are installed after each non-negligible change of state.

The fuel cell stack used is the HyPM HD8 which is manufactured by the company Hydrogenics Corporation. The stack consists of 80 cells each with a polymer electrolyte. The maximum electrical power that can be achieved is equal to 8.4 kW. The voltage varies between 80 V ($U_{max}$) and 40 V ($U_{min}$) and the maximal current amounts to 200 A ($I_{max}$). The voltage-current characteristic given by the manufacturer is shown in Fig. 5.

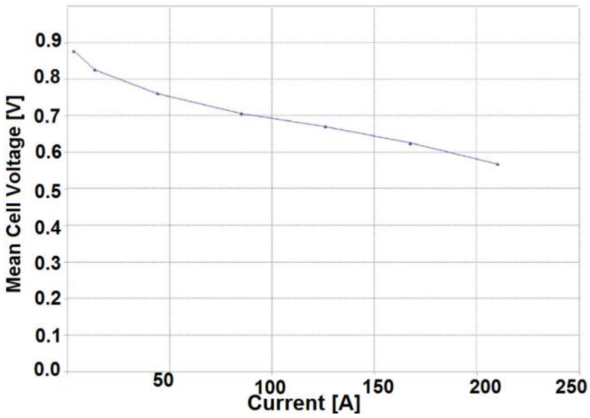
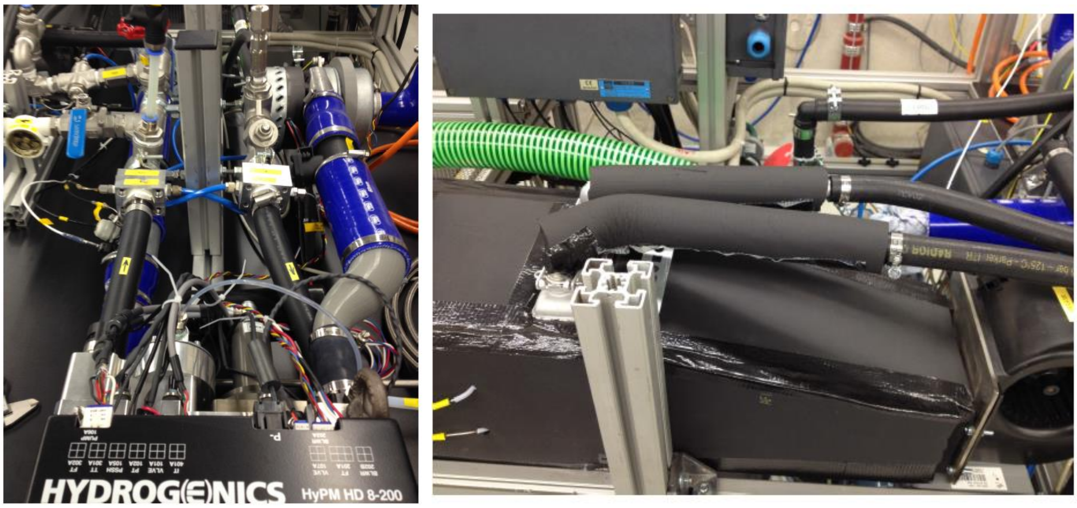



Figure 5: Typical HyPM HD8 Performance

Electrically, the fuel cell system is coupled to a DC electronic load which is intended to function as an electrical load and thus consumes electrical power of the fuel cell. In order to operate the fuel cell according to a specific load profile, an arbitrary waveform generator is connected to the DC electronic load that specifies to the user how much electrical power is to be extracted from the fuel cell. The generator converts the desired signals into a voltage signal which is used as an input signal for the DC electronic load.

During operation the hydrogen is fed continuously into the stack. The hydrogen mass flow rate is measured with a CMF Coriolis mass Flowmeter (accuracy ±0.35% of the measured value). The absolute hydrogen pressure at the inlet of the fuel cell is set to 5.5 bar an checked with the highly precise pressure Transmitter 33XEi ( accuracy of Δp = ±0.06 bar). The oxygen is fed into the fuel cell electrodes via an air supply ventilation system, which consists of a fan and air ducts. Fig. 6 (a) shows the blue air ducts of the air supply system and the black pipes of the cooling system.




(a) Air ducts and coolant pipes of the fuel cell HyPM HD8

(b) Model of the air conditioning cabinet

Figure 6: A/C-APU test bench

An air mass flowmeter (accuracy 0.1% of the measured value) and a temperature sensor Pt100 (accuracy ±(0.15 + 0.002*T) are installed in the air section in front of the fuel cell. The ambient pressure and relative humidity (RH) are measured with a HMT360 transmitter (±1% RH, ±0.1 °C). These measurement staffs allow the exact detection of the thermodynamic state of the incoming air. By means of sensors in the air section downstream of the fuel cell, the thermodynamic state of the outlet air can also be determined. Thus, using the first law of thermodynamics, an enthalpy balance is established and the resulting heat flux is analyzed analytically.

In order to maintain stable fuel cell operation, it is necessary to ensure a continuous cooling of the fuel cell stack. Continuous cooling is carried out using a liquid cooling system with a water-glycol mixture. In order to dissipate the heat energy absorbed by the fuel cell to the environment, the cooling system is equipped with the vehicle cooler of the Smart ForTwo ED and the associated vehicle fan. The rotation speed of the fan is controlled by an integrated operating strategy of the fuel cell system and thus the heat is emitted convectively to the environment depending on the fuel cell power and temperature. In parallel with the vehicle cooler, a coolant/air heat exchanger is integrated into an adiabatic chamber, which contains an electric fan, an air mass flowmeter and temperature sensors before and after the heat exchanger. In addition to these components, a positive temperature coefficient heater (PTC) is integrated into the adiabatic chamber. The electric PTC heater is switched on in order to obtain a desired temperature in the adiabatic chamber. Additionally, the waste heat of the fuel cell is carried out into the adiabatic chamber by ventilating the heat exchanger. Fig. 6 (b) shows this chamber on the test bench, which represents the air conditioning cabinet of a passenger car.

In a next phase, the test benchs for the 8 kW PEM fuel cell and the MeH cooling system will be coupled to an overall A/C-APU demonstrator. The goal is to proof the concept of the A/C-APU and carry out various tests in an environment similar to real vehicle operating conditions. Furthermore, using power and temperature measurements, the controllability and the separation of the traction and air conditioning will be analyzed on system-level and appropriate operating strategies will be developed and demonstrated.

# 4 Experimental Investigation

In this section, a summary of the experimental results of the single reactor measurements as well as the proof of concept with two alternately working reactors of the open cooling system are presented. The corresponding results are described more in detail in [3][4].

The characterisation of a single plate reactor in non-continuous experiments (sensible losses neglected) showed that very short half-cycle times in the range of 60-90 s are feasible [3]. According to Fig. 7, for a heat transfer fluid temperature of $T_{\mathrm{in}} = 20$ °C and a desorption pressure of $p_{\mathrm{des}} = 1.013 \cdot 10^5$, an average specific cooling power of $\bar{\dot{q}}_{60\,s} = 1.7$ kW $\mathrm{kg_{MeH}}^{-1}$ can be reached. These values, that are more promising than state of the art reactor concepts, make the reactor concept appropriate for the AC/APU. The characteristic specific cooling power profile in Fig. 7 is a result of the decreasing reaction rate with growing transformed mass fraction and reduced distance to the thermodynamic equilibrium. With a constant hydrogen mass flow rate due to the coupling with a fuel cell, the cooling power profile should get more homogenious.

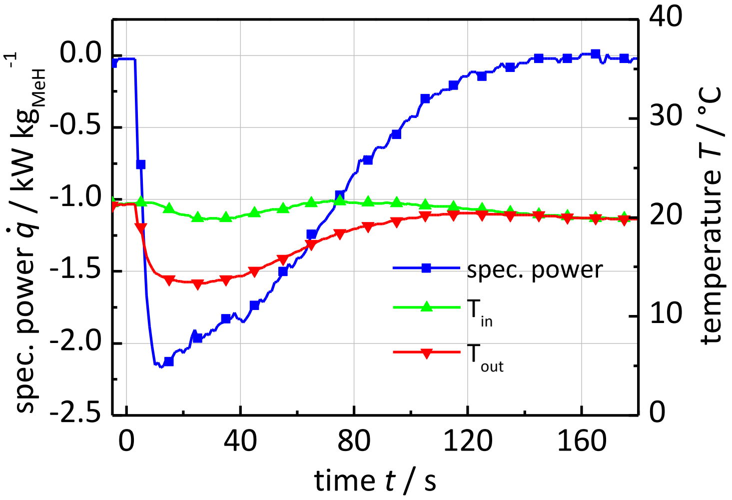



Figure 7: Results of a single desorption experiment for $\mathrm{p_{des}} = 1.013 \cdot 10^5$ Pa with $\mathrm{T_{in}} = 20$°C (green, ▲), $\mathrm{T_{out}}$ (red, ▼) and spec. power (blue, ■) [3].

Subsequently, with two alternating metal hydride reactors a proof of concept of the open cooling system is conducted in the setup shown in Fig. 4. The calculated heat fluxes for the reactors R1 (blue) and R2 (turquoise) for a constant inlet temperature of $T_{in} = 10\,°C$ are shown in Fig. 8. For negative values of the heat flux, a constant average cooling power of -532 W for a fixed half-cycle time of 100 s can be determined. With regard to the small scale reactors with a metal hydride mass of around 335 g, this value corresponds to 1.59 $kW\ kg_{MeH}{}^{-1}$. Since the small lab-scale reactors exhibit a high sensible to active mass ratio of $m_{sys} \cdot m_{MeH}{}^{-1} = 5.5$, these values are clearly reduced when an ambient temperature of 35 $°C$ is considered.

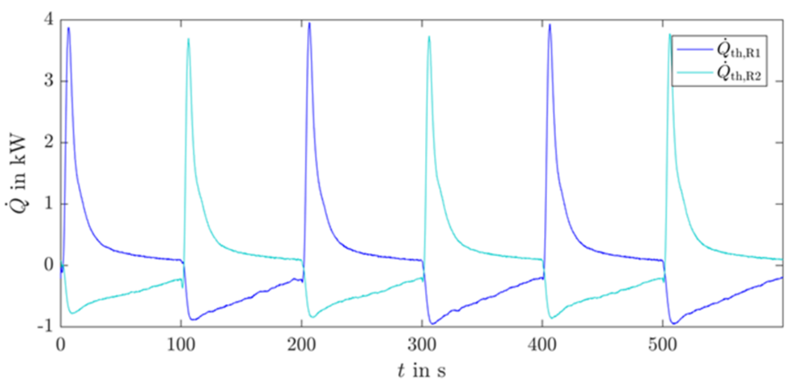



Figure 8: Results of the continuous working system for $\mathrm{p_{abs}} = 27 \cdot 10^5$ Pa, $\mathrm{p_{des}} = 1.013 \cdot 10^5$ Pa and $\mathrm{T_{in}} = 10$°C

In a next step, the small lab-scale reactors will be up-scaled and constructed for an average cooling power of 2 kW. By up-scaling the ratio of passive to active mass will decline to around 2.5- 3 and as a result the sensible loses will be reduced. These reactors will be coupled with a 8 kW PEM fuel cell and it will be experimentally demonstrated which cooling power can be achieved depending on the hydrogen consumption of the fuel cell. Additionally, it will be shown which cooling temperatures are achievable.

## 5 Numerical investigation

For overall vehicle simulations a one-dimensional model of the metal hydride reactor is developed based on reaction kinetics of the absorption and desorption processes as well as the mass and energy balances in the metal hydride and coolant [5]. In order to validate the numerical model, absorption and desorption measurements were performed. The boundary condition of the test set-up are summarised in the Table 1. The hydrogen pressure is set to 30 bar in the absorption cases and to 1 bar in the desorption cases. The coolant temperature upstream of the reactors was varied and amounted to 50 °C, 30 °C and 10 °C.

Table1: Boundary conditions for the experiments

| | $T_{HTF\_In}$ [°C] | $\dot{V}_{HTF}$ [l/min] | $p_{H2}$ [bar] |
|---|---|---|---|
| Absoprtion | 30 | 4.9 | 30.7 |
| Absoprtion | 50 | 9.6 | 30 |
| Desorption | 30 | 4.34 | 1 |
| Desorption | 50 | 5.6 | 1 |
| Desorption | 10 | 4.5 | 1 |

The comparison between simulation and experimental results are shown in Fig. 9. The thermal output is plotted over time. The black line presents the measured thermal power, which is calculated with the measured temperatures at the inlet and outlet of the reactor as well as the water flow rate. The simulated power is shown as a solid red line in the same Figure. The positive power values indicate a cold production and the negative values indicate a heat generation.

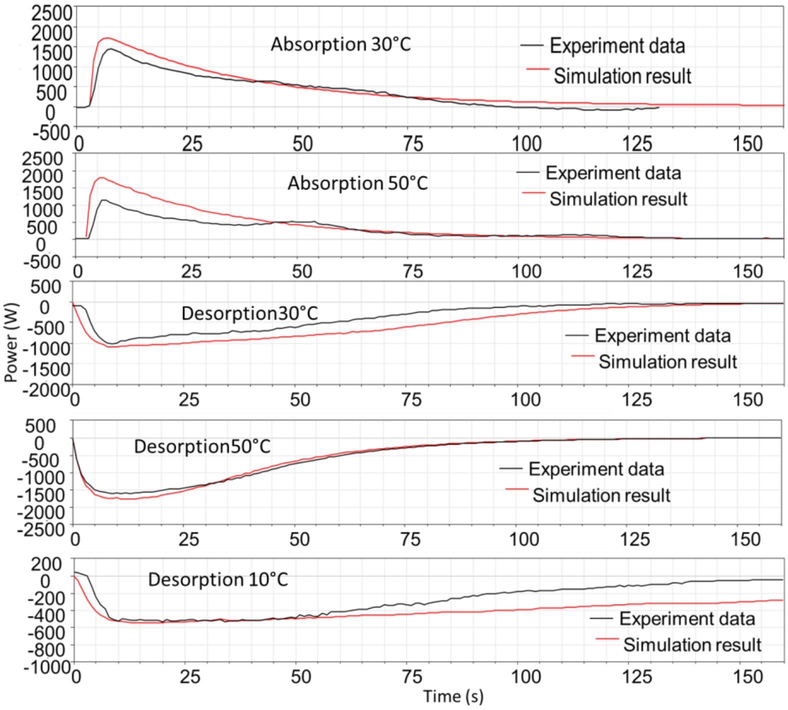



Figure 9: Model predictions of experimental power histories during absorption and desorption

It can be clearly seen that in the absorption simulations (two upper diagrams), the peak load is slightly overestimated. The cooling power in the desorption simulations is very well estimated and shows negligible deviation. Therefore, it can be summarized that the 1D model is capable to describe the dynamical behaviour of the metal hydride reactor under different boundary conditions in an accurate way with the same parameter set.

To determine the behaviour of the MeH cooling system in fuel cell vehicles, modeling was performed using an overall vehicle simulation model developed in [6]. A fuel cell range extender vehicle developed by the DLR Institute of Vehicle Concepts is simulated. This car is based on the e-powertrain of the Smart Fortwo vehicle [7] manufactured by Daimler AG and uses a fuel cell as a range extender unit (FC-REX). The installed fuel cell is the liquid cooled HT PEM (High temperature polymer electrolyte membrane) stack S165L manufactured by the company Serenergy [8]. Using pure hydrogen the fuel cell generates a rated net power of 6 kW.

The energy consumption of the thermal management system (HVAC and tempering system) as well as the vehicle consumption are shown in Table 2 for two driving cycles EcoTest [9] and Großglockner [10] at high ambient temperatures. The EcoTest cycle is designed by the Europe's largest automobile club (ADAC) for the evaluation of electric vehicles and includes a NEDC, an Artemis Driving Cycles (CADC) and a special ADAC motorway cycle. The Großglockner cycle present a travel at constant speed along the Großglockner High Alpine road.

Table 2: boundary conditions and results of the overall vehicle Simulations

| | Ambient temperature [°C] | Range [km] | Vehicle consumption [kWh] | Thermal energy demand for climate control [kWh] | Electricity consumption of the thermal management [kWh] |
|---|---|---|---|---|---|
| EcoTest | 35 | 35.5 | 12.3 | 2.31 | 2.28 |
| Großglockner | 35-18 | 18.3 | 8.8 | 0.5 | 0.8 |

Using a 6 kW fuel cell, the cooling power of the MeH cooling and heating system shown in Fig. 10 corresponds to 20% of the fuel cell electrical power [11]. Consequently, for the ADAC driving cycle 0.65 kWh of the thermal energy for the cabin cooling could be generated by the hydrogen-based system. Assuming that the COP (**C**oefficient **o**f **p**erformance) of the refrigeration cycle is equal to 2, an electrical energy of 0.32 kWh (14% of the electricity consumption) could be saved. In the case of the Großglockner driving cycle, an electrical energy of 0.05 kWh (6.3% of the electricity consumption) could be saved.

With the installed 6 kW fuel cell 1.2 kW of cold are maximally generated by the MeH cooling and heating system. For a cooling capacity of 1.2 kW, the total weight of the reactors is about 9 kg with a volume of 2.5 l. Under these conditions, the simulation results in [10] showed that an integration of the MeH cooling system into the FC-REX vehicle for continuously support of the HVAC leads to increase the vehicle range by more than 8% at 40 °C ambient temperature.

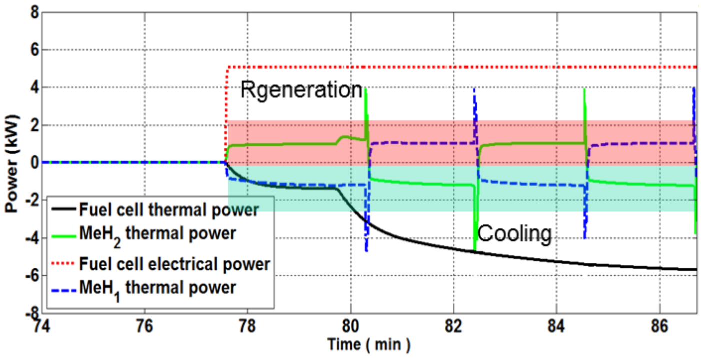



Figure 10: Simulation results of the MeH cooling system integrated into the fuel cell range extender vehicle developed by the DLR Institute of Vehicle Concepts [11].

# 6 Conclusion and Outlook

In this work, an air-condtitioning and auxiliary power unit (A/C-APU) is presented. The A/C-APU is used for vehicle thermal management as well as for increasing the range of battery-powered electric cars and hydrogen fuel cell vehicles. The main components of the A/C-APU are a hydrogen pressure tank, a fuel cell and a hydrogen-based cooling and heating system which converts potential energy from the pressurized hydrogen into cold and heat using two alternately working compact metal hydride (MeH) reactors. With the A/C-APU it is possible to reutilise up to 75% of the compression work that is spent at the filling station.

For the MeH cooling and heating system, the MeH reactors are the critical components to realise a small and compact system. In order to avoid heat transfer limitations, a novel plate reactor is constructed that allows half-cycle times for a complete transformed fraction in the range of 60 s – 90 s. The reactor concept was examined experimentally through a test bench that presents a part of the complete AC/APU setup including a 8 kW PEM fuel cell.

For numerical investigation of the A/C-APU, a one-dimensional simulation model of the tested metal hydride reactor is developed and validated with measurement data. The reactor model is used for the modelling of the MeH system which is integrated into an overall vehicle simulation model to evaluate the A/C-APU in fuel cell vehicles.

The results show that the cooling power of the A/C-APU is approximately one-fifth of the the electrical power. In case of a fuel cell range extender vehicle developed by the DLR Institute of Vehicle Concepts, the replacement of the installed fuel cell by a A/C-APU with the same electrical power leads to an electrical energy saving of up to 14 percent according to the repetition in sequence of three driving cycles (NEDC, CADC, freeway) and a range increase by up to 8% according to NEDC in hot wheather conditions.

The next step is to demonstrate proof of concept of the A/C-APU by means of the complete A/C-APU setup including a 8 kW PEM fuel cell and two MeH reactors with an average cooling power of 2 kW. The performance of the A/C-APU at the vehicle-level, especially in cold weather conditions, needs to be further evaluated. In particular it should be investigated wether the power consumption to heat the passenger compartment can be covered by the waste heat of the fuel cell and the MeH cooling and heating system when operated as a heat pump.

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