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Integration of a PEM fuel cell with a metal hydride tank for stationary applications

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Abstract

An integrated power system of a PEM fuel cell and hydride tanks designed for stationary applications is described. The work was focused on different aspects related to the development of the metal hydride tank and to its integration with the fuel cell, using water as thermal fluid. A commercially available $LaNi_{4.8}Al_{0.2}$ intermetallic compound was chosen as hydrogen storage material, having sorption characteristics adequate to the working conditions of the system (i.e. 60 °C and 1 atm). Tanks were constituted by stainless steel, together with copper fins for improving heat exchanges between the thermal fluid and the tank. The performances of the integrated system were tested in different working conditions, in order to evaluate its reliability and efficiency. The system can operate for about 6 hours, at an average power of 0.76 kW and delivering a total energy of 4.8 kWh, consuming about 3120 Nl of H_2.

Keywords

Intermetallic metal hydride, Fuel cell, System integration, Hydrogen storage

1. Introduction

Renewable energies such as wind and solar power are considered nowadays promising alternative energy sources due to the decreasing availability of fossil fuels and to a reduced production of pollutants during energy exploitation. A disadvantage of these sources is the non constant production of energy during the day or the year due, for example, to changes in weather conditions or to the night and day cycle. Therefore, it is of interest to explore new methods of storage of the excess of energy in order to use it when a decreased production is acting. Moreover, there are areas in which there is a lack in the energy power supply such as mountain huts or remote islands. In

these cases, it is of interest to design new energy storage units alternative and more sustainable with respect to conventional diesel electric generators [1, 2].

Hydrogen is considered as an energy carrier and its chemical energy can be converted into electricity through a chemical reaction with oxygen from a fuel cell. Therefore, coupling energy storage systems with renewable energy sources through an electrolyser, that can transform electric energy into hydrogen chemical energy, is considered as an high sustainable process of production and exploitation of renewable energies [3]. In literature, examples are reported of integrated systems constituted by a metal hydride tank and a PEM fuel cell, in which the waste heat generated in the fuel cell is used to supply the necessary heat required for desorption of hydrogen from the tank [4, 5, 6, 7]. In other systems, the hydrogen storage unit is not thermally integrated with the fuel cell, as reported by Bossi et al. where a PEM fuel cell, a battery bank, a metal hydride hydrogen storage unit and an electronic load was integrated [8].

This work describes the development of an integrated power system designed for stationary applications, constituted by a commercial Proton Exchange Membrane (PEM) Fuel Cell and a metal hydride tank. The field of application of the integrated power system is in combination with renewable sources: the hydrogen can be produced by electrolysis of water using the energy from a renewable source (e.g. photovoltaic); it is then stored and converted into electric energy by the proposed integrated power system, that allows to store energy in the form of hydrogen and then to reuse it when the renewable source is not available, for example at night if solar power is exploited. The developed power system could replace batteries and could be applied in case of a production plant not connected to the power grid, such as in remote areas. In this work, the design of the tank will be described in details, together with the description of the P&I of the integrated power system and corresponding tests, showing a total energy production of 4.8 kWh, over more then 6 h of working activity.

2. Experimental

As storage material, $LaNi_{4.8}Al_{0.2}$ intermetallic compound produced by Palcan Energy Corporation, China was selected. Pressure-Composition-Isotherm (PCI) measurements were performed at different temperatures, from 25°C to 100°C on different batches of the same intermetallic compound. PCIs have been performed over the 0 – 100 bar pressure range using about 1 g of sample in a volumetric apparatus by Advanced Materials Corporation, Pittsburgh PA. This instrument is equipped with a sample cell of 2 ml volume and a temperature controller that provides corrections for ΔT between hydrogen reservoir and specimen holder. Hydrogen absorbed amounts are calculated using modified Benedict-Webb-Rubin equation for real gases. Prior to performing

PCI measurements, the alloy was coarse grinded and then activated following this general procedure for two times: i) in-vacuum heating to 100 °C; ii) soak in 100 bar hydrogen pressure at 100°C for one hour; iii) cooling down to room temperature.

Desorption tests were performed on one of the six metal hydride tanks constituting the integrated system. Tests were performed at 60°C with a laboratory test bench. When the equilibrium temperature was reached, the valve was opened in order to let the hydrogen to be released and to flow outside the tank at a pressure of 1.5 bar. The flow of hydrogen was controlled and regulated using a mass flow controller set at 2.67 Nl/min for each tank, corresponding to 1/6 of the H_2 flow necessary to operate the fuel cell at its maximum power. The mass flowmeter was also used to measure the amount of hydrogen released from the tank. The pressure inside the cylinder was monitored by a pressure sensor.

The PEM fuel cell used for the power integrated system is a BALLARD FC-GEN1030V3 with water cooled stacks, designed for domestic applications with the following characteristics: maximum power of 1.246 kW; current of 0 - 40 A; tension of 31,1 – 46 V; hydrogen flow necessary to operate the fuel cell at the maximum power of 16 Nl/min; hydrogen pressure of 240 mbar; air flow of 50 l/min; air pressure of 150 mbar; water inlet temperature of 57 °C; water outlet temperature of 67 °C.

3. Results and discussion

3.1 Metal hydride characterisation

In order to design the integrated power system, it is first of all necessary to evaluate the quantity of energy that has to be stored, being needed by the final application. In our case, a small system is designed with a commercial PEM fuel cell with power of 1.246 kW, water cooling stack and operating temperature of about 60 - 70 °C. In order to simplify the heating/cooling circuit and the absorption/desorption processes, the cooling water of the PEM FC was used for increasing the temperature of the tank and driving the hydrogen desorption. Therefore, the choice of the storage material was strictly connected to the requested desorption temperature, defined to be around 60°C. AB5 type materials already available on the market were chosen for this application [9, 10, 11]. Different producers were contacted in order to determine prices, performances and reproducibility characteristics of the intermetallics. The intermetallic compound $LaNi_{4.8}Al_{0.2}$ was selected as storage material and characterised in order to assess its operating performances in real conditions. Moreover, a control on the reproducibility of its absorption/desorption characteristics was carried out in order to determine the reproducibility of the H_2 release, in view of a possible commercialization of the power integrated system. Therefore, PCI measurements were performed

for different production batches. A comparison of PCIs collected at 60°C is reported in Fig. 1. They show reproducible behaviour, with a maximum gravimetric density of about 1.4 wt% H_2. Values of ΔH and ΔS for absorption and desorption were obtained by a Van't Hoff plot and the results are reported in Tab. 1 for the different batches measured.

In order to determine the amount of hydride powder necessary for the construction of the integrated system, it was first of all necessary to calculate the amount of H_2 necessary to guaranty the operation of the PEM fuel cell at its maximum power for at least 4 h, knowing that an H_2 flow of 16Nl/min is required by the PEM fuel cell. The needed volume of H_2 results to be 3840 l and the corresponding amount of intermetallic powder is about 25 kg, being the maximum gravimetric density of $LaNi_{4.8}Al_{0.2}$ of about 1.4 wt%. The quantity of the metallic hydride was increased to 29 Kg in order to have spare H_2 to guaranty the operation of the fuel cell for at least the time required by the application. To size the tanks of the integrated system, it is necessary to determine the total volume occupied by the intermetallic, from the alloy density, that is about 5.8 l when the alloy is in powder form. Moreover, an empty volume necessary for the expansion of the powder while forming the hydride have to be considered. Therefore, the volume of the tank was increased of the 20% with respect to the volume of the powder, obtaining a total storage volume of about 7.0 l that was divided into six tanks.

3.2 Design of the metal hydride tank and of the storage system.

The design of the metal hydride tank was defined after a survey on the literature, patent and commercial available hydride tanks [12, 13, 14]. The materials used for the tank are essentially aluminium and stainless steel. They are mostly cylindrical in shape and sometimes equipped with heat exchanger in order to improve the efficiency of the change in temperature of the powder during heating and cooling, i.e. H_2 release and absorption. A major problem in the tank construction is in fact the poor thermal conductivity of the storage material, that is reported in literature to be in the range of 0.1-0.6 W/m K for non compacted powders [15, 16]. The cylindrical shape for the tank, in fact, is the simplest and involves low volumes and low weight, but also a low surface for the heat exchange, that has to be increased by adding heat exchangers in the tank.

In order to determine the better design for the tank, a simulation was made by finite element analysis, using the COMSOL Multiphysics approach, on the absorbtion and desorption of hydrogen, taking mainly into account the heat exchange of the powder and of the tank [17]. The optimized geometry is reported in Fig. 2. The tank is cylindrical in shape, it is filled with the hydrogen storage powder and a sintered steel tube is inserted along the tank. The hydrogen flow inlet is in the upper part of the tank, and H_2 flows trough the sintered tube, enabling a large contact surface between H_2

and $LaNi_{4.8}Al_{0.2}$ powder and a homogeneous distribution of the gas in the powder volume. A heat exchanger, made on polypropylene, is positioned on the external part of the tank, enabling a homogeneous cooling and heating of the powder, during sorption and desorption.

The entire storage system is composed by six tanks of equal size and geometry. The units are independent and ensure 1/6 of the flow rate needed to operate the fuel cell at its maximum power.

In the design and materials selection of the storage system, the following parameters were evaluated: i) the material compatibility mainly with respect to the hydrogen embrittlement, permeability and mechanical strength; ii) thermal exchanges and sizing of the heat exchangers. The whole system was designed according to the existing European and Italian standards (EN, VSR and Ispesl norms) [18]. The design phase has been concluded with a detailed drawings ready for the manufacturing of the storage system.

3.3 Metal hydride tank desorption tests

In order to complete the storage system design, tests were performed on one of the six tanks with the aim to check the charging time and the H_2 flow during discharging.

During the test, performed maintaining the heating water at 60°C, the H_2 flow rate was set at 2.67 Nl/min for 220 min, with the release of 61% of the H_2 stored in the tank. Afterward, the flow rate decreased. The PCI desorption of H_2 at 60°C compared with the desorption of hydrogen from the tank during the test is reported in Fig. 3 (star symbols and triangles respectively). The pressure in the tank during the desorption test appears lower with respect to the PCI equilibrium pressure. This result is due to a non efficient thermal exchange between the thermal fluid and the hydride powder, which temperature was determined to be 55°C. Therefore, a metallic spiral was added around the tank, in order to increase the water flow and allow a more homogeneous heat exchange from the fluid to the surface of the tank. Moreover, copper fins were inserted in the sintered tube in contact with the intermetallic powder in order to increase the heat exchange in the whole mass of the powder. After adding these parts, the desorption test was repeated and the result is shown in Fig. 3 (square symbols). A significant increment in the pressure was registered, confirming the increase of the heat exchange in the tank that guarantees a more efficient thermal management during the hydrogen desorption.

3.4 P&I

The system is composed by two separate sections: the fuel cell circuit with its components that constitutes the power generation part and the hydrogen storage part, mainly constituted by the six metal hydride tanks.

The P&I of the whole system is reported in Fig 4. The fuel cell circuit is composed by the circulation pump (M1), the heat exchanger (heat 4) necessary to remove the power in excess and to heat the fuel cell during the start-up, the air compressor (M3), the humidifier for air (HY1) and hydrogen (HY2). The hydrogen circuit is composed by the circulation pump (M4), the hydrogen storage cylinders (B1...B6), the heating/cooling flow controls device (FL1.6), the heat exchanger (heat1) necessary to remove the heat generated during the charging of hydrogen, the safety valve (PSV1), the pressure reducer (reg1) and the monitoring of the pressure and temperature. The two circuits are joined by a plate heat exchanger (heat3). All the components are driven and monitored by a PLC with a software interface developed for the application.

3.5 Tests on the power integrated system

The integrated power system was tested in laboratory, by dissipating the current produced during the test with an electronic power. The system worked for more then 6 h, at an average power of 0.76 kW. For 2 h the system provided a power of 1 kW (Fig. 5). The total energy provided by the PEM fuel cell was 4.8 kWh and the net power available was 3.06 kW, considering a loss of about 290W consumed by the system equipments for 6 h, i.e. 1.74 kWh. The total amount of H_2 consumed was of 3120 Nl. The H_2 was delivered to the mass flow controller with a pressure of 1.5 bar and the H_2 flow (Fig. 5) increases in the first 100 min for remaining then stable for more then 2 h, while the stack voltage remains almost stable during the whole test.

4. Conclusions

An integrated power system was constructed, mainly constituted by a commercial fuel cell and a storage system with six tanks. The tanks were designed for the integration with the PEM fuel cell and the cooling water of the PEM fuel cell was used for increasing the temperature of the storage powder in the tank and starting the hydrogen desorption. The storage material used was $LaNi_{4.8}Al_{0.2}$ and the reproducibility of the sorption/desorption characteristics of various batches was determined by PCI measurements. During desorption tests, almost all the hydrogen stored in the tank was desorbed. The integrated power system can work for more than 6 h providing an average power of 0.76 kW.

Acknowledgments

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Figure captions

Fig. 1: PCI measurements on different batches of $LaNi_{4.8}Al_{0.2}$. Open symbol are due to hydrogen desorption while full symbols are due to hydrogen absorption

Fig. 2: Schematic representation of the hydride tank

Fig. 3: PCI desorption (star symbols) in comparison with hydrogen desorbed from the first designed tank (triangles) and the second designed tank (square symbols)

Fig. 4: P&I of the power integrated system

Fig. 5: Power (square symbols) produced from the integrated system during a test together with H2 flow (triangle symbols) and stack voltage (star symbols) is reported versus time.

Tab. 1 Values of ΔH and ΔS for absorption and desorption obtained by a Van't Hoff plot. The different batches are reported.

***Highlights (for review)**

- Integrated power system with a commercial fuel cell and a hydrogen storage system
- Tanks were designed for the integration with the PEM FC
- During desorption tests, almost all the hydrogen stored in the tank could be desorbed
- The integrated power system can work for 6 h providing an average power of 0.76 kW

Table 1

	Absorption		Desorption	
	ΔH (kJ/mol)	ΔS (J/mol*K)	ΔH (kJ/mol)	ΔS (J/mol*K)
Batch 1	-34.0	111.4	38.2	121.4
Batch 2	-30.7	102.0	38.7	122.9
Batch 3	-31.9	105.3	35.0	111.5
Batch 4	-31.5	104.3	38.8	122.7
Average	-32.1 ± 1.4	105.7 ± 4.0	37.7 ± 1.8	119.6 ± 5.4

Tab. 1 Values for the different batches of ΔH and ΔS for absorption and desorption obatined by a Van't Hoff plot

Figure 1

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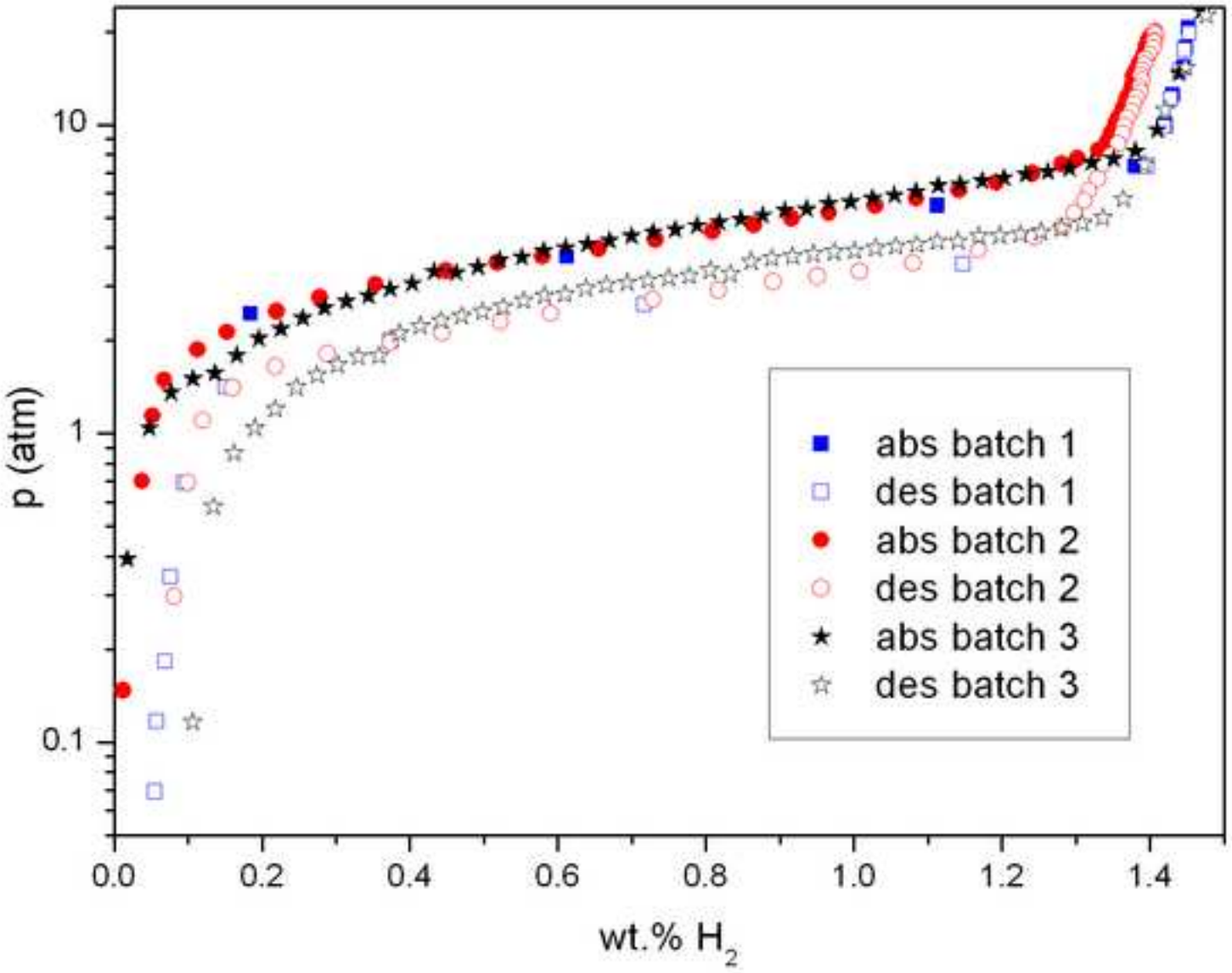

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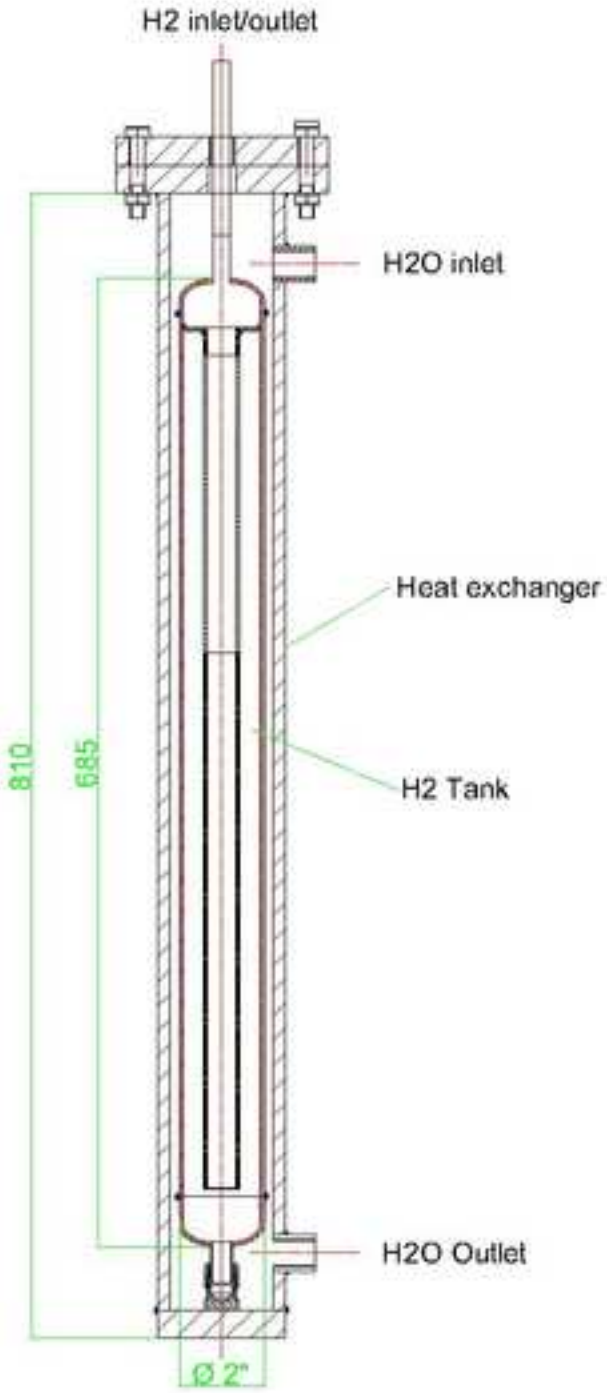

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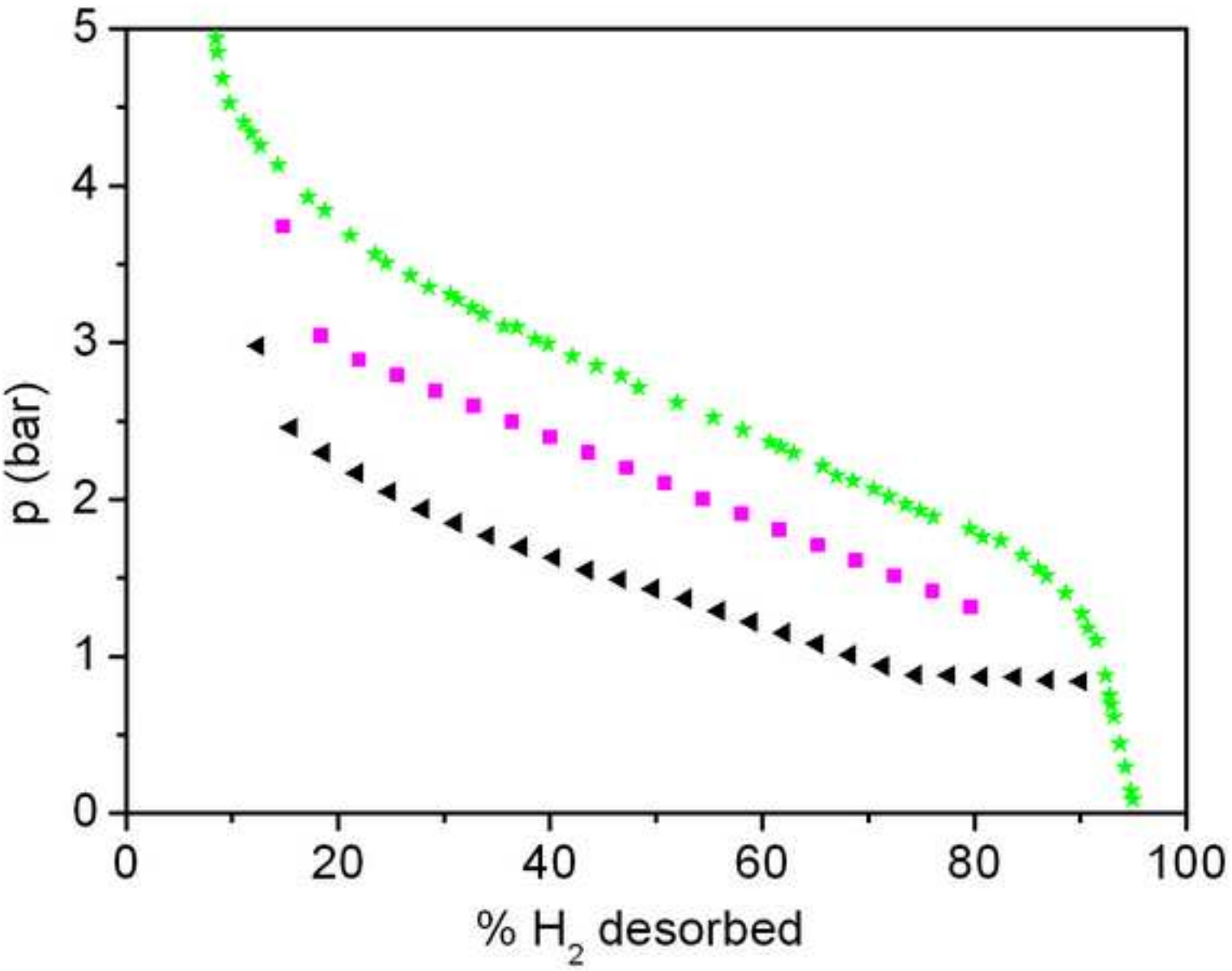

Figure 4

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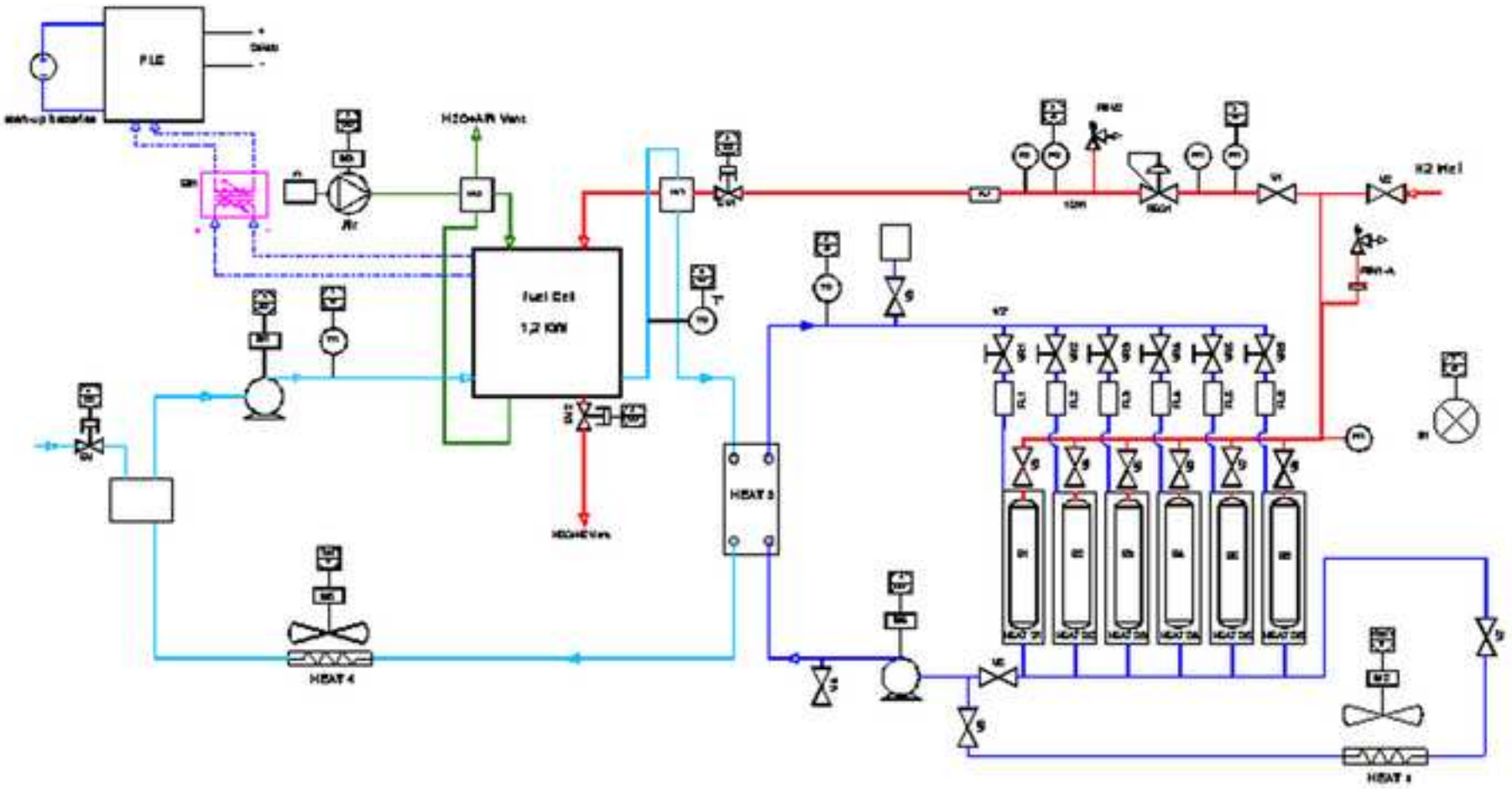

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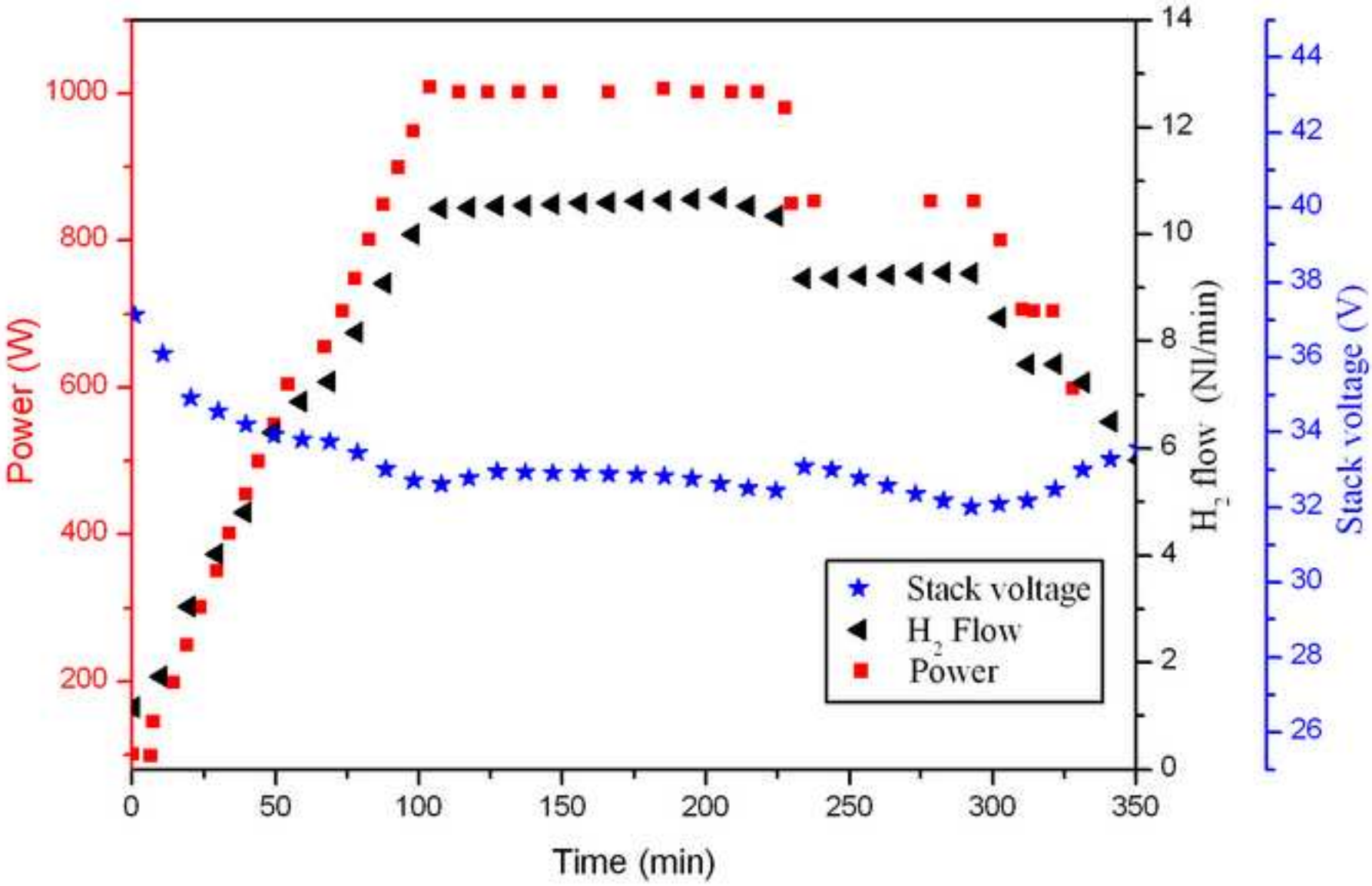
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