Hydrogen fueled stove for autarkic living

Hydrogen fueled stove integrated in the EMPA self sufficient building SELF

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Zusammenfassung   Abstract

Kochen für autarkes Wohnen ist weiterhin eine energetische Herausforderung. Im Sommer ist elektrisches Kochen mit PV Strom möglich, im Winter ist dies jedoch in unsern Breitengraden problematisch. Das Speichern von grossen Mengen elektrischer Energie in Akkumulatoren für das Kochen im Winter würde eine sehr grosse Kapazität erfordern. Deshalb ist die Umwandlung von Überschussenergie mittels Wasserelektrolyse in Wasserstoff vorteilhafter. Beim Speichern von Wasserstoff in Metallhydriden entstehen keine Verluste vom Wasserstoff. Wandler und Speicher sind zudem getrennt, damit können geringere Systemkosten erreicht werden. Dient Wasserstoff als Energieträger, so besteht die Möglichkeit, diesen direkt in Wärme um zu wandeln. Zu diesem Zweck wurde ein neuartiger katalytischdiffuser Wasserstoffbrenner, basierend auf einer hoch porösen Siliziumkarbid (SiC) Keramikplatte mit Platinbeschichtung entwickelt, der hervorragend zum Kochen benutzt werden kann.

Cooking is one of the remaining challenges in autarkic living. In summer electric cooking from PV is well possible. Nevertheless, long term battery storage to cover the energy demand for electric cooking in winter is not feasible. A superior approach to seasonal PV energy storage is the production of hydrogen by water electrolysis and storage thereof in metal hydrides. With this approach no hydrogen loss is encountered during storage time, volumetric energy density is increased and storage capacity is decupled from power conversion potentially reducing storage cost. When considering hydrogen as energy carrier the possibility of direct conversion to heat by catalytic oxidation becomes practicable. To this accord a novel catalytic diffusion burner for hydrogen, based on highly porous silicon carbide (SiC) ceramic foams, coated with platinum (Pt) as catalyst has been developed and integrated into a cooking stove.

1. Scope

For the Empa mobile self-sufficient living and working unit SELF (Fig. 1) a hydrogen based stove has been developed [1]. SELF serves as a research and demonstration platform for novel building and energy technology systems [2]. The unit furnishes users with all common living comforts. Electric power is provided from PV panels and rain water is collected and purified for drinking water as well as reused for technical water. Key challenges faced in SELF are the continuous electric energy and water supply. Fluctuations in the supply of electrical power and water have to be backed by on board storage, whereby seasonal fluctuation demands large storage capacities.

The SELF electrical storage system functions as a hybrid system. It is composed of lithium ion batteries for diurnal storage and a hydrogen storage system for seasonal storage. Excess electric energy is converted to hydrogen using a small PEM hydrogen generator from the Swiss company Schmidlin with an output of 1 Nl/min (norm liter per minute). Hydrogen is stored in metal hydrate cylinders and converted to electricity on demand using a 1 kW PEM fuel cell from the Swiss company MES(Fig.2) [2].

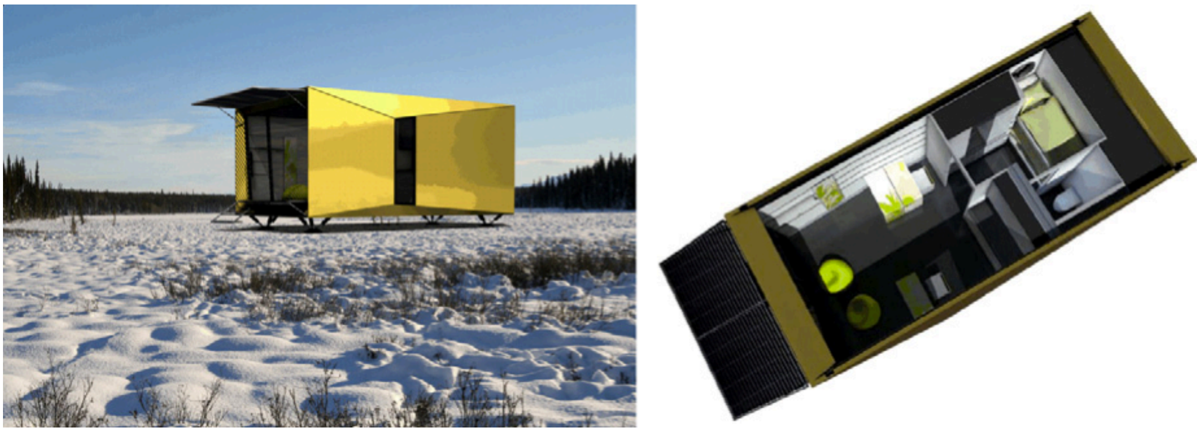

Figure 1: SELF stand-alone living unit. System size: 3.5m×7.5m×3.2m (W×L×H). The roof accommodates the photovoltaic power plant for energy production.

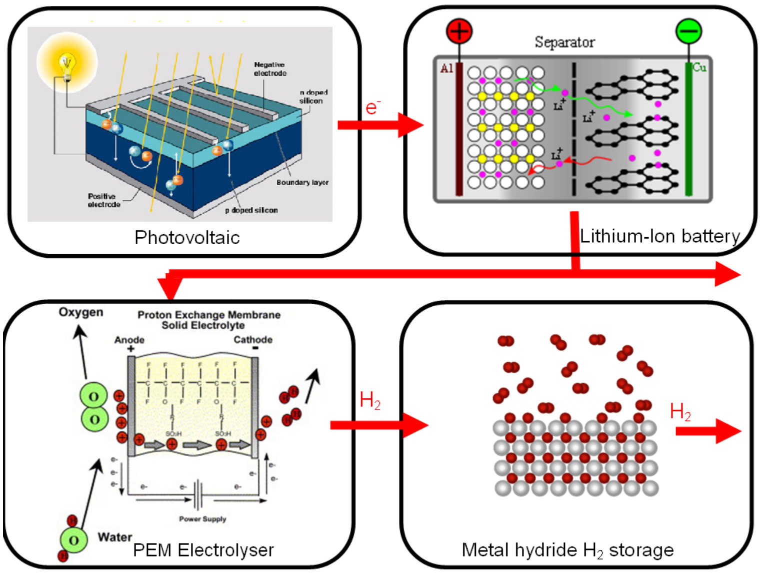

Figure 2 SELF energy cycle: solar radiation is converted to electrical energy and stored in batteries, surplus energy is used to produce hydrogen, stored in metal hydrides alloy AB5 from JMC.

SELF is furnished with a fully functional kitchen, including sink, refrigerator, dishwasher and hydrogen based cooking stove. Due to the high energy consumption in cooking and the lack of sufficient solar energy harvesting in winter, electric cooking is not feasible in this setting. In order to support all year round cooking a hydrogen fuelled stove was developed. Summers excess energy harvest, stored as hydrogen can so be accessed as cooking fuel. In this approach, compared to electric cooking via fuel cell in winter, higher conversion efficiency is achieved. Naturally cooking efficiency would be higher in summer by using an electrical stove (efficiency between 74% to 84%), nevertheless efficiency is not demanded during high energy availability, but in shortage. In order to reach high cooking comfort, the hydrogen burner was covered with a standard glass ceramic stovetop (Fig. 4 and cover photo).

Catalytic hydrogen burner development

Hydrogen readily oxidizes in contact with platinum and oxygen [3]. While this is favorable for conversion to heat, critical safety issues are to be paid attention to. Due to the broad range of Flammability (4-75%), premixing hydrogen and oxygen prior to oxidation can easily lead to uncontrolled combustion in the mixing chamber. In order to avoid premixing, an approach where hydrogen and air are supplied from separate sources to the catalytic active combustion area was adopted. Catalytic hydrogen combustion can reach temperatures of up to 1000°C. Thus, in addition to an appropriate catalyst, a sufficient carrier material is required. Silicon carbide ceramic has a high temperature stability and good thermal shock resistance. In order to allow hydrogen and air to be supplied from varying sources to the combustion area, reticulated porous silicon carbide ceramic (RPC) was chosen [4]. These highly porous SiC plates are coated with platinum as catalyst to ensure a catalytic combustion reaction. In this way, hydrogen can be supplied from the bottom of the porous SiC plate and air from the top. Fuel and oxidant thus mix only in the porous combustion area. Uncontrolled combustion is prevented and high passive safety measures are reached. Hydrogen is immediately oxidized by the redox reaction of hydrogen with oxygen [5] by the following reaction:

$$2\ H_2(g) + O_2(g) \xrightarrow{\text{catalyst}} 2\ H_2O(l) + 572\ \text{kJ} \quad (1)$$

The process of hydrogen combustion emits neither carbon oxides nor nitrogen oxides making this form of heat conversion favorable for save indoor applications. From the exothermic reaction sufficient heat is produced for cooking purposes.

Through the catalytic combustion any active ignition such as a spark, required by other gas fuelled stoves, becomes obsolete. The catalytic oxidation of hydrogen in the porous SiC ceramic has the benefit of omitting no open flame. The burner design consists of two overlying porous SiC plates, each with catalytic coating, separated with a SiC based porous air diffuser. Hydrogen is supplied from below into an expansion chamber and penetrates through a highly porous diffuser whereby it is evenly spread below the active SiC area. On the surface of the main porous catalytic area the hydrogen reacts at the triple point H_2-O_2-Pt according to equation (1). Air is forced to the reaction zone in between the first and second catalytic area. The second catalytic area serves to oxidize any remaining hydrogen in order to prevent hydrogen slip through the upper catalytic SiC plate. The hydrogen diffuser is designed smaller in diameter in relation to the reaction zone to prevent hydrogen from escaping through the rim of the diffuser prior to oxidizing.

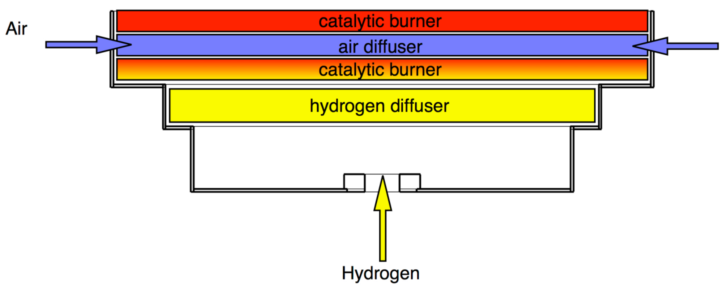

Figure 3: Catalytic diffusive hydrogen burner setup. Hydrogen is supplied from below, air is supplied between the 2 catalytic areas.

Hydrogen stove development

In the development of the hydrogen stove a hydrogen burner as described above was integrated into a specially designed casing and covered with a glass ceramic top. A heat exchanger was included to preheat the incoming air with the exhaust air leading to a significant improvement in efficiency and reduction in exhaust temperatures (Table 2). The exhaust air and water vapor is released through the exhaust tube below the inner casing as demonstrated in figure 4. The complete system is fastened to the glass ceramic top and can be integrated into a kitchen counter top. Common thermal safety features as implemented in an electric glass ceramic stove were used. Thus a temperature safety switch was placed above the burner to prevent excess temperature above 600°C. Power regulation was achieved with a common stove switch producing a slow PWM signal in dependence of the power setting. Power is thus not regulated by continuous hydrogen flow regulation, but by switching hydrogen and air flow on and off. Figure 5 shows the stovetop assembly. The left CAD drawing shows an expanded view of the stove. Starting from the top is the glass ceramic plate followed by the standard temperature safety switch, the hydrogen burner and heat exchanger, the inner casing and the outer casing. The complete stove has a volume of 400 mm by 290 mm by 94 mm.

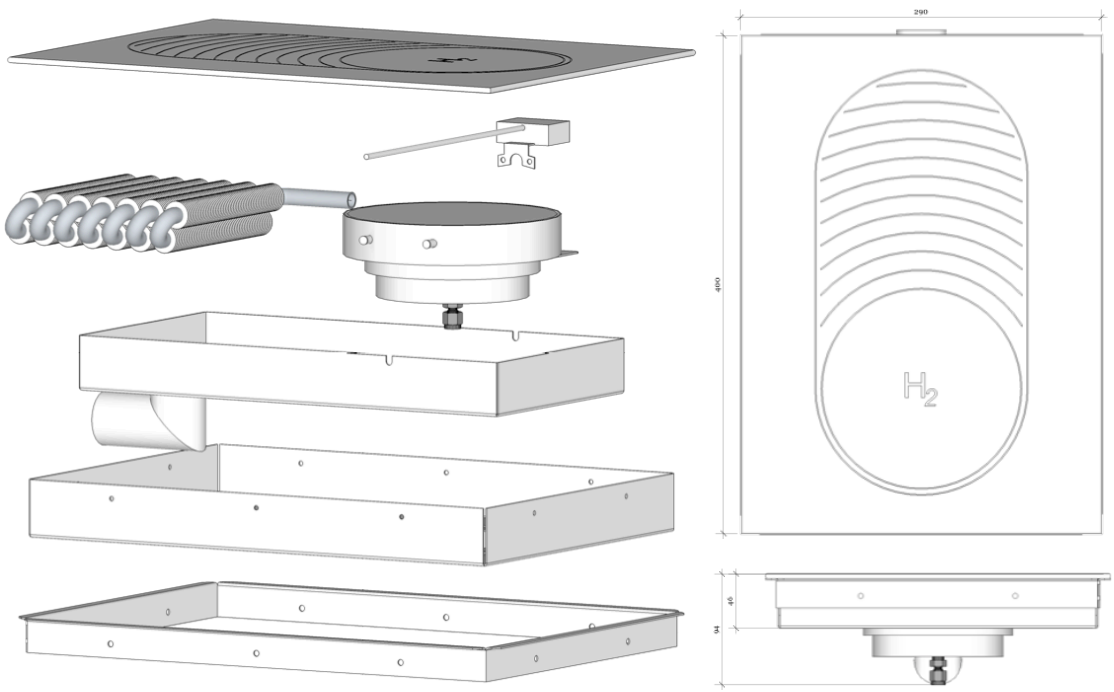

Figure 4: Left: Expanded picture of the hydrogen stove. Right: Outer dimensions of the hydrogen stove.

2. Methods and results

In order to improve the oxidation process, which in turn increases the area specific power density necessary for a cooker, a concept with forced air supply is required (Fig. 3) [6]. Thus higher air and hydrogen flows can be realized, achieving higher overall area specific power ratios. Table 1 shows the burner area specific power in dependence of the hydrogen flow for an active burner area of 176 cm^2.

Hydrogen flow	Lower heating value	Area specific power	Air flow λ = 3
[Nl/min]	[W]	[W/cm^2]	[Nl/min]
2	356	2	15
4	720	4	30
6	1080	6	45
8	1440	8	60
10	1800	10	75

Table 1: Heating values, area specific power in respect to the hydrogen flow rate. Air flow for λ = 3, SiC burner plate diameter = 150 mm.

In this approach, the airflow can be quantified and specific ratios of air to hydrogen evaluated. While a stoichiometry of λ=1 is the minimum ratio of oxygen to hydrogen required for the complete oxidation reaction, in practice a lambda ratio of 2-3 is used.

To verify safe operation, the hydrogen slip during operation must be tested. This refers to the amount of hydrogen passing the catalytic porous burner without oxidizing. Hydrogen slip occurs mainly due to inadequate distribution of oxygen on the catalytic burner plate or insufficient air lambda values. A low hydrogen slip improves safety aspects and is an important issue concerning total efficiency [7].

For quantifying the hydrogen loss, online mass spectrometry was used to analyze the exhaust gases. The quantification is done in parts per million (ppm) of hydrogen in the exhaust air. Testing was carried out to distinguish the optimal air to hydrogen ratio in respect to hydrogen slip and SiC burner temperature as well as glass ceramic surface temperature. Hydrogen flows of 2 Nl/min to 8 Nl/min were tested with lambda values of 1.5 to 3, as shown in figure 6. These testes were done with the forerunner design of the final stove shown in figure 5. Nevertheless the measurements are comparable. The best results concerning H_2 slip as well as surface temperature could be reached with λ ≥ 2.

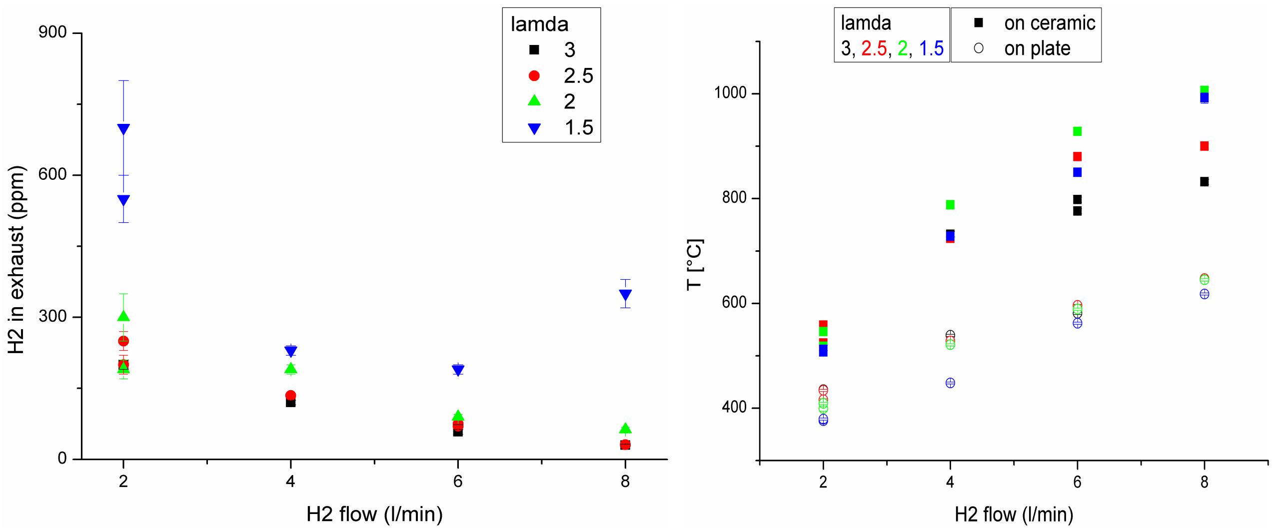

Fig. 5: Left: Dependence of hydrogen slip vs. hydrogen flow at different lambda values. Right: Temperature on the SiC ceramic (on plate) and on the glass ceramic (on ceramic) in relation to hydrogen flow and λ values.

Figure 7 shows the effect of self-ignition of hydrogen. The tests are carried out with a hydrogen flow rate of 8 Nl/min and λ = 3, corresponding to an actual air flow of 60 Nl/min. Just after starting the reaction, the initial hydrogen slip was determined by 18’000 ppm (1.8 vol%) which is still considerably below the lower ignition limit of 4 vol% hydrogen in air. As the catalytic coated SiC foam reaches 585 °C, self-ignition occurs inside the porous SiC structure. Hydrogen oxidation now takes place by catalytic combustion on the platinum coated porous SiC ceramics and by thermal catalyzed combustion. This leads to a further improvement in the oxidation of hydrogen and thus reduces the hydrogen slip in the exhaust gas to values below 50 ppm. At the point of self-ignition, a rise in temperature on the SiC surface can be observed. The burner plate surface levels at approximately 850°C while the glass ceramic surface reaches the maximum temperature of 600°C.

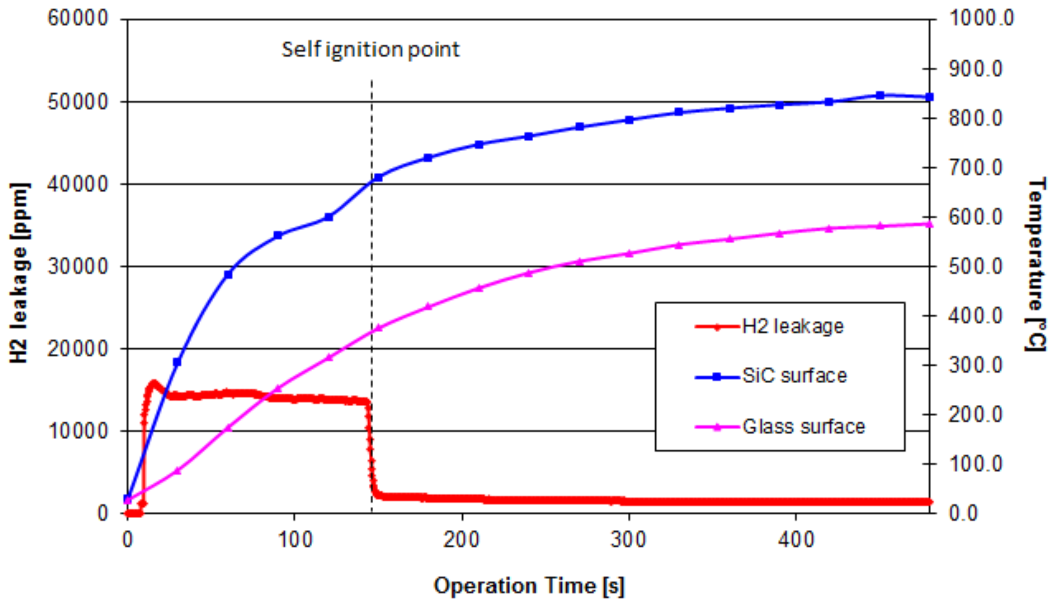

Figure 6: Temperature over time, H_2 leakage and self ignition point for a H_2 flow rate of 8 Nl/min and λ = 3.

Efficiency tests were carried out according to DIN EN 30-2-1 [7]. This standard deals with home cooking stoves based on gaseous fuels. The testing procedure consists of heating 3.7 kg of water in a pot with an inner diameter of 220 mm from 20 ± 1 °C to 90 ± 1 °C. The minimum cooking efficiency by the DIN norm is set to be 52% for gas stoves. As pointed out, to improve the overall efficiency of the hydrogen stove, a heat exchanger was implemented. Incoming air is preheated via heat exchanger by the exhaust air. Tests have been carried out with heat exchanger and glass ceramic cover as well as without heat exchanger and/or glass ceramic cover to compare the corresponding efficiencies.

The efficiency tests were done at hydrogen flow rates of 6 Nl/min, 7 Nl/min and 8 Nl/min (Table 2). Based on the lower heating value, the efficiency was found to be 59% without heat exchanger, 66% for the complete setup with heat exchanger and glass ceramic and 70% with heat exchanger but without glass ceramic plate.

Hydrogen flow	Air flow	Power (LHV)	Efficiency (LHV)	Setup
[Nl/min]	[Nl/min]	[W]	[%]	-
6	2	1079	66	glass ceramic and heat exchanger
7	2	1259	66	glass ceramic and heat exchanger
7	2	1259	59	without heat exchanger
7	2	1259	70	without glass ceramic
8	2.4	1439	64	glass ceramic and heat exchanger

Table 2: Cooker efficiencies for different set ups and H_2 flow rates, λ = 2.0 respectively 2.4.

3. Discussion and perspectives

In this research and development project a safe hydrogen fueled catalytic burner was built up and integrated into the EMPA SELF building as a fully functioning glass ceramic stove top. This approach permits all year round carbon free autarkic cooking independent of the momentary available solar radiation.

By preventing premixing of hydrogen and air, safe operation is achieved and due to the absence of carbon and the relatively low temperatures below 1000 °C no hazardous gases are expelled.

An efficiency of 66 % could be reached. This is considerably higher than the standard for conventional gas stoves which is approximately 56 % or what could be reached using a fuel cell and electric stove which would be only approximately 35 %.

The results from the tests conducted throughout this research project have proven the possibility of using hydrogen for all year round autarkic cooking. This approach is able to match safety, efficiency, performance and convenience of commercially available gas- or electro stoves.

4. Acknowledgement

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