Development of a Novel Cooking Stove Based on Catalytic Hydrogen Combustion

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Catalytic hydrogen combustion; hydrogen based cooking; gas under glass technology.

Abstract

A hydrogen based cooking stove was developed and tested in respect to efficiency, functionality and hydrogen safety. The therefore developed novel combustion unit technology is based on the catalytic oxidation of hydrogen on a platinum coated highly porous reticulated silicon carbide foam ceramics. Compared to other works [1], premixing of hydrogen and oxygen is avoided, thus providing the basis for safe and reliable operation. With this catalytic combustion technology, no initial hydrogen ignition is required, implying a high application security. Separate air and hydrogen supplies make regulation of temperature and power efficient, simple and save.

Catalytic hydrogen oxidation is performed already at room temperature; whereby at high hydrogen load, a small hydrogen slip is detected under cold start conditions, nevertheless in operation this becomes negligible. In order to overcome this issue, a hydrogen flow regulation, based on the hydrogen combustion temperature, was introduced.

A heat exchanger is integrated into the exhaust line, in order to recover heat for the incoming air, required for the catalytic combustion. This leads to a stove efficiency of up to 80 %, measured according to the DIN EN 30-2-1: 2005-08 test standard and greatly exceeds the postulated standard minimum efficiency of 35 %. For comfortable and save use, the combustion unit is mounted under a glass ceramic coverage, as common for conventional electrical stoves.

Introduction

In the frame of the development of a mobile autarkic living unit, able to cover both its electricity and water demand through atmospheric input, a novel hydrogen (H₂) fuelled cooking stove was developed. This development enables self-sufficient renewable cooking with highly efficient H₂ conversion. The stove operation is based on the catalytic oxidation of H₂ with oxygen (O₂) from air on the surface of a platinum (Pt) coated porous silicon carbide (SiC) foam ceramics [2, 3].

The living unit called SELF is furnished with a photo voltaic (PV) generator and both, batteries for short-term (diurnal) electricity storage and H₂ for long-term (seasonal) energy disposability [4]. H₂ is produced by a PEM electrolyser (NMH2-1000HP from Schmidlin) with a H₂ output of 0.8 NI/min (NI = norm litre) and stored with metal hydride technology (type AB₅ from Japan Steel Works) with a total H₂ capacity 50'000 NI. A PEM fuel cell (DEA 1.0 from MES) is installed to regain electricity from stored H₂ if required.

Especially when resorting to the seasonal storage during solar supply deficit, as common in central and northern European winter seasons, energy efficiency is crucial. For cooking purposes, direct conversion from H_2 to heat has the potential for a higher efficiency than by conversion from H_2 to electricity for electrical cooking. Efficiency for direct H_2 oxidation depends solely on the heat conductivity from the point of oxidation to the cooking pot. In times of sufficient solar radiation, requiring an intermediate step of water electrolysis is naturally less efficient than electric cooking from batteries. Nevertheless, in a closed unit such as SELF represents, efficiency is of primary importance only during supply deficit, in our case in winter season, where transfer of stored energy from summer into winter is necessary. Efficiency losses by water electrolysis can be neglected in as far as the annual energy harvest is adequate.

Through catalytic H_2 oxidation for cooking rather than electric cooking from stored H_2 via fuel cell, a reduction in the required nominal fuel cell power output and the necessary H_2 storage capacity for seasonal storage is reached. This leads to overall system cost reductions.

The process of H_2 oxidation for cooking utilization is unpretentious in terms of temperature and power regulation as well as cost, in respect to materials and equipment required.

Furthermore, by catalytic oxidation of H_2 [5], no CO_x or NO_x is emitted due to the lack of carbon and the low oxidation temperatures below 700 °C [6].

Intensive work has been carried out on low temperature catalytic combustion for the residential utilization of H_2 in order to eliminate pollutants. Predominantly the H_2 and air premixing approach is followed. Huratu [7] and Schefer [8] have done fundamental studies on low-temperature catalytic combustion in future H_2 energy systems for H_2 and air pre-mixtures.

Only very limited work is available on catalytic H_2 combustion without H_2 and air premix technology, meaning separate feeding of H_2 and air directly to the combustion area. Dahm et al. did important work in 1977 [9] in which he proposed such a system. He has done a series of experiments and modelling, but the system has never been commercialised. A non-stationary H_2 cooker was also proposed by Großmann et al. [10] with a series of finger like porous H_2 distributors with “self respiring” technology. This system has a relatively low area specific power output, as there is no forced and regulated air supply system. The new developed system proposed in this paper has large potential for a highly scalable, powerful, clean and save cooking stove technology.

When looking beyond the current application in SELF, a large application potential of such H_2 powered cooking stoves is identified not only for autarky living, but also in novel building energy clusters, remote areas, alpine huts and related applications.

Experimental: Set-up and stove architecture

Important design criteria in the H_2 fuelled stove development were easy operation and intuitive handling, as well as compliance to modern kitchen technology. Furthermore, control of the stove must not demand any special knowhow allowing the user to be completely indifferent to the heat source. Consequently, a gas under glass design with a common glass ceramic cover as typically used for electric kitchen stoves was aspired. The basic combustion unit design consists of a stack of 4 highly porous (> 90%) SiC foams, as shown in figure 1 and described in detail in the noted references and patent [2, 11]. Porous SiC foam ceramics are used as carrier for the catalytic Pt support due to the high temperature stability and good thermal shock resistance. Details on SiC foam production and testing are reported in the noted reference [12]. In this application, SiC ceramic foams from Lanik s.r.o (SZ) were used. For catalytic H_2 combustion, the SiC ceramic foams were coated with a β - Al_2O_3 washcoat to increase the SiC foam surface area and Pt for the catalytic oxidation reaction. Coating was performed by Infragas srl (I), details of the catalytic reaction are described in the noted reference [3].

In the newly developed assembly, H_2 is supplied from below the combustion area and diffuses upwards through the SiC ceramic foam. As shown in [figure 1](#), SiC foam 1 serves as H_2 diffuser with a pore size of 100 pores per inch (ppi). This SiC foam has no catalytic coating and serves to evenly spread the H_2 over the succeeding catalytic coated SiC foam 2, which has a pore size of 80 ppi and is catalytic active. SiC foam 3 has a pore size of 40 ppi and enables a homogeneous air distribution. Air is supplied from the side as indicated in [figure 1](#) and spread evenly across the active combustion area. SiC foam 4 is the second catalytically active reaction zone with a pore size of 60 ppi. This final Pt coated SiC foam serves to oxidise any remaining H_2 in order to reduce H_2 slip from the preliminary reaction zone. In summary, H_2 reacts in contact with Pt and O_2 from the air on the surface of the Pt coated SiC foams 2 and 4 [\[11, 13\]](#).

The combustion unit has an active area of $2 \times 176 \text{ cm}^2$. H_2 is supplied to the stove via pressure reduction valve, mass flow regulator (Vögtlin 124137, Range 0.3 to 15 NI/min, Accuracy $\pm 1\%$ of max. value) and 2/2 way normally closed (NC) solenoid valve. Air is supplied to the reaction zone by an air pump (Alita Linear Air Pump, AL-40) and is measured by a Vögtlin mass flow meter (Type 125185, Range 4 to 400 NI/min, Accuracy $\pm 1\%$ of max. value).

The complete combustion unit inner casing is built of stainless steel 1.4404 sheets of 1 mm thickness ([Figure 2](#)). A copper fin tube heat exchanger is included to preheat the incoming air with the exhaust air and water vapour, leading to a significant improvement in efficiency and simultaneously reducing outbound air temperatures. The surplus air and water vapour is released finally through the exhaust tube below the inner casing as shown in [figure 2](#). The complete system is fastened to a glass ceramic cover and can easily be integrated into conventional kitchen counter tops.

The stove is facilitated with several hard-wired safety features. A NC thermal safety switch is implemented between the combustion unit and the glass ceramic stove top, shown in [figure 2](#), as used in conventional electric based glass ceramic stoves. The switch precedes the NC H_2 valve and cuts the power supply to the valve upon temperatures above 700°C . This temperature limit was chosen to ensure thermal stability of the glass ceramic cover as well as to prevent thermal aging of the Pt catalyst. A normally open (NO) air pressure switch is mounted in line with the thermal switch. The switch closes upon detecting air supply from the air pump, thus allowing H_2 supply to the combustion zone only when air supply is guaranteed. A H_2 sensor (Neodym, Hydro-Knows) is placed in the exhaust stream to detect any H_2 slip. This sensor has an integrated relay, which again is looped into the H_2 valve power supply. If the H_2 content in the spent air exceeds 2 %, which is half of the lower ignition level of H_2 in air, power supply to the H_2 valve is cut and the valve closes. The stove dimensions are 400 mm deep, 290 mm wide and 94 mm high. The expanded drawing is shown in [figure 2](#).

The combination of catalytic H_2 combustion and gas under glass technology brings forth several key benefits. Due to the catalytic combustion technology, ignition is not required and combustion temperatures can be well adjusted through independent H_2 and air supply. Surplus air and formed water vapour are confined and can be guided through the heat exchanger and exhaust tube to the atmosphere.

The stove was tested in respect to stove efficiency and H_2 release in the exhaust air, referred to as H_2 slip.

The efficiency test was performed according to the standard procedure given in the DIN EN 30-2-1: 2005-08 test standard [\[14\]](#). This convention describes the testing procedure for gas-fuelled stovetops. The standard allows two test cases, cold start and hot start, for practical reasons, the hot start procedure was followed.

Tests were done with a H_2 flow of 7nl/min and 8nl/min and lambda values (λ), the ratio of oxygen (O_2) to H_2 , of 1.5, 2.0 and 2.5. The resulting nominal power output in respect to H_2

flow is 1.2 kW and 1.4 kW respectively. This power range requires a cooking pot with 220 mm diameter and a water capacity of 3.7 kg, tests were done with the pot lid closed. The following testing procedure described in the DIN standard and abided to in this examination, was used. Initially, the stove is preheated with a test pot containing 3.7 kg of water at $20 \pm 1^\circ\text{C}$. The stove is considered preheated once the water has reached boiling temperature. Directly upon removing the preheating pot, the actual test pot with identical dimensions, water content and initial temperature is placed on the now preheated stove and the test is started. The H_2 flow [l/min], water temperature and time elapsed is determined. Upon reaching a water temperature of $90 \pm 1^\circ\text{C}$ the test is stopped. The pot remains on the stove, and the highest reached water temperature after turning the stove off is taken for the efficiency calculation.

The efficiency is calculated as the ratio of the energy uptake of the pot and potted water. Calculation was done in respect to the water mass equivalent of the pot and content and the change in temperature, to the total energy released from the stove, equivalent to the H_2 mass consumed multiplied by its heating value. The lower heating value for H_2 (33.3 kWh/kg) is taken and the efficiency is calculated according to:

$$\eta = 4.186 \times 10^{-3} m_e (t_2 - t_1) / (V_c \times H_s) \times 100 \text{ (Equation 1) [14]}$$

η = Efficiency in per cent

m_e = Equivalent mass of pot

The equivalent mass of the pot is calculated as follows:

$$m_e = m_{e1} + 0.213 m_{e2}$$

m_{e1} = mass of the water in the pot

m_{e2} = the mass of the aluminium pot including lid. The value is multiplied in equation 1 by 0.213 in order to get the water mass equivalent

t_1 = Initial temperature of the water ($20 \pm 1^\circ\text{C}$)

t_2 = Final temperature of the water

V_c = Volume of gas used

H_s = Heating value of the gas

Two testing procedures were followed in order to test the H_2 content in the exhaust excess air released from the stove. First, the H_2 slip was measured during the turn on phase, at varying combustion-starting temperatures. Hereby the H_2 flow was kept at 8 NI/min and air to H_2 ratio at λ 2. Second, the H_2 slip was measure during stable operating conditions with varying H_2 flows from 3 NI/min to 8 NI/min and λ values of 1.5, 2 and 2.5.

A H-Sense mass spectrometer (Type 04 04 151, Calibration gas 4999ppm $\pm 2\%$ H_2 in N_2) was used to quantify the H_2 content in the released air. The H_2 sensor probe was positioned at the stove exhaust (Figure 2) and the temperature sensor was placed on the top centre of the secondary catalytic combustion zone 4 (Figure 1).

Figure 1: Setup of diffusive catalytic H₂ combustion unit with Pt coated SiC foams of different pore sizes. H₂ is supplied from beneath the SiC foam layers and air is supplied between the two catalytic active SiC foams. The combustion unit has an active area of 2 x 176 cm².

Figure 2: CAD drawing of the stove main components, expanded for clear illustration.

Results and discussion

Figure 3 shows the test results of the efficiency measurements. The measured efficiencies are above 70% for all measuring conditions with a maximum of 79.6% at a hydrogen flow of 7 NI/min and $\lambda = 1.5$. All results are high in respect to the minimum efficiency regulation for gas stoves with gas below glass technology which is defined to be > 35 % according to the DIN standard. The best results are reached with low λ values. This is due to the reduction of heat loss by heat transport from the combustion zone through excess air. In addition, the performance of the heat exchanger is expected to be better at low air flow. Compared to previous testing results without heat exchanger it can be noted that the heat exchanger improves the overall efficiency by an average of 19 %. There is room for improvement on the heat exchanger performance; nevertheless, due to the near equality of incoming air mass to outbound air mass, it is not possible to reach condensation of the reaction water vapour on the heat exchanger. It follows that the lower heating value of H₂ is the maximum energy conversion efficiency. The respective maximum gravimetric energy density of H₂ is 33.3 Wh/g. The results further point to a sufficient rate of oxidation even at a λ value of 1.5. Possible efficiency reduction due to lower oxidation of hydrogen resulting in increased hydrogen slip is not detected. At a combustion temperature of 629 °C the spent air temperature departing the heat exchanger has a temperature of 68 °C at a H₂ flow of 8 NI/min and $\lambda = 2$.

Figure 4 shows the results of the determined H₂ slip in the turn on phase. At 100°C starting temperatures a H₂ slip of 2.1% was detected which is still below the critical lower ignition limit of 4 % H₂ in air, but slightly above our set safety limit of 2 %. At 200 °C the H₂ slip rapidly decreases to 0.41% with a continuous decrease, ending up with 0.01% at 600°C. A steep drop in the detected hydrogen quantity was seen starting at a combustion

temperature of 150 °C. In cooking, the combustion area temperature is kept above 150 °C, promoting a low hydrogen slip.

Figure 3: Diagram of the efficiency tests in respect to H₂ flows of 7 NI/min and 8 NI/min and lambda values of 1.5, 3, 3.

Figure 4: Diagram of H₂ slips, measured in respect to starting temperature of the combustion unit at a constant H₂ flow rate of 8 NI/min and lambda 2. The H₂ slip is indicated in % H₂, measure in the exhaust air.

In continuous operation, the H₂ slip is very low, as shown in **figure 5**. The diagram shows the H₂ content in the surplus air in ppm at varying H₂ flows and respective combustion temperatures. The circle centre indicates the temperature, resulting from the applied H₂ flow, and the circle diameter indicates the H₂ slip measured. Slightly higher H₂ slip is found at lower λ values. This is possibly due to the reduced H₂-O₂-Pt contact resulting from declined availability of O₂. Nevertheless, the corollary lower dilution of slipped H₂ by excess air is expected to be the more dominant factor. Further, very slight H₂ increase is detected at low H₂ flows, which can be accounted for by the lower combustion temperatures.

In order to reduce the H₂ slip at low combustion temperatures during the starting phase, a dependency of H₂ flow to combustion temperature at constant airflow was included in the control strategy. In this way the H₂ slip in the surplus air is kept low by increasing the surplus air to slipped H₂ ratio. From the test results the function shown in **figure 6** was determined as:

$$\text{H}_2 \text{ flow} = f(T) \times \text{Air flow} \quad (\text{Equation 2})$$

Figure 7 shows the resulting H₂ slip in the initial heat up phase as a dashed line, the dotted line shows the respective H₂ flow and the solid line shows the inevitable temperature

increase. Starting at room temperature, a low H₂ flow rate of 1 NI/min is supplied to the catalytic area while the air flow is kept constant at 40 NI/min. The H₂ flow is steadily increased as the combustion temperature increases. This in turn leads to a more rapid temperature increase. Initially a maximum H₂ slip of 1.5 % H₂ in the exhaust air can be determined. The H₂ slip swiftly decreases with increasing combustion temperature due to improved catalytic activity above room temperature. Once the combustion temperature reaches 150 °C the gain in H₂ flow increases rapidly, leading to a slightly higher peak of H₂ slip. As the combustion temperature surpasses the self ignition temperature of H₂ with O₂ of 536 °C, H₂ slip becomes negligible. The pulsing of the H₂ flow, also resembled in the combustion temperature after 500 sec. is due to the temperature control set to 650 °C and does not increase H₂ slip since combustion temperatures are high.

Figure 5: Diagram of the H₂ slip in continuous operation, in respect to H₂ flow rate, lambda value and resulting combustion temperature. The circle centre indicates the combustion temperature at a set H₂ flow and the circle diameter shows the H₂ slip given in ppm.

Figure 6: Diagram of the H₂ flow as function of the combustion temperature.

Figure 7: The diagram shows the combustion temperature (solid line), the corresponding H₂ flow (dotted line) and the determined H₂ slip (dashed line) of the regulated stove in the initial heating up phase and at operating conditions.

Conclusion

A novel design of a catalytic H₂ based cooking stove has been successfully developed and implemented into the mobile self-sufficient living unit (SELF). A rugged design was established, demonstrating a high safety standard and allowing straight forward stove handling.

In relation to the minimum efficiency of 35% for gas under glass stoves set by the DIN norm, high efficiencies up to 80% could be reached. It is found that lower air flows result in a higher efficiency due to the increase in heat transfer on the heat exchanger and the reduction in heat transport from the combustion unit surface by the surplus air. The slightly higher H₂ slip is assumed to derive from the lower dilution as well as lower O₂ availability resulting from the lower air flow rates. It could be shown that nearly complete catalytic reaction occurs already at room temperature and improves at elevated temperatures. A H₂ slip of up to 2.1 % could be detected only during start-up conditions at low temperatures and high H₂ flow rates (8 NI/min). Even so, this is still well below the lower ignition limit of 4 %. H₂ slip during the heat up period can be diminished to very low values through reduction of H₂ flows. In continuous operation a very low H₂ slip below 1 ppm could be detected which is far beneath the set safety limit of 2 %. The implemented temperature dependent H₂ flow control is able to keep the H₂ slip far below the ignition limit of 4% H₂ in air during the heat up phase as well as during continuous operation.

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