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Compact propane fuel processor for auxiliary power unit application

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Abstract

With focus on mobile applications a fuel cell auxiliary power unit (APU) using liquefied petroleum gas (LPG) is currently being developed at the Centre for Fuel Cell Technology (Zentrum für BrennstoffzellenTechnik, ZBT gGmbH). The system is consisting of an integrated compact and lightweight fuel processor and a low temperature PEM fuel cell for an electric power output of 300 W.

This article is presenting the current status of development of the fuel processor which is designed for a nominal hydrogen output of 1 kW_{th,H_2} within a load range from 50 to 120%. A modular setup was chosen defining a reformer/burner module and a CO-purification module. Based on the performance specifications, thermodynamic simulations, benchmarking and selection of catalysts the modules have been developed and characterised simultaneously and then assembled to the complete fuel processor.

Automated operation results in a cold startup time of about 25 min for nominal load and carbon monoxide output concentrations below 50 ppm for steady state and dynamic operation. Also fast transient response of the fuel processor at load changes with low fluctuations of the reformate gas composition have been achieved.

Beside the development of the main reactors the transfer of the fuel processor to an autonomous system is of major concern. Hence, concepts for packaging have been developed resulting in a volume of 7 l and a weight of 3 kg. Further a selection of peripheral components has been tested and evaluated regarding to the substitution of the laboratory equipment.
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Keywords: Fuel cell; Auxiliary power unit; Fuel processor; Liquefied petroleum gas; Catalytic burner; Peripheral components

1. Introduction

At the Centre for Fuel Cell Technology (ZBT) a fuel cell auxiliary power unit (APU) with an integrated fuel processor and a low temperature PEM fuel cell is currently being developed. The APU is designed for using liquefied petroleum gas (LPG) which is mainly a mixture of propane and butane but the fuel processor can also be adapted to other gaseous hydrocarbons like natural gas. A multitude of application areas have been identified for small-scale electric generators with an electric power output between 100 and 500 W considering LPG as fuel. Camping and caravanning, boats and small yachts as well as remote systems show a high potential for penetrating the market with a fuel cell APU. For a straightforward market introduction a fuel has been chosen which is commercially available within a world wide infrastructure. For example, in the European Union LPG is currently offered for sale in cylinders, as refill of stationary tanks for remote applications off the electric grid and as fuel for vehicles at selected petrol stations. Compared to, e.g. hydrogen or methanol as alternative fuels in the future, LPG is already available and commonly used for many applications.

For the LPG based APU a first application could be the on-board electric power supply for small yachts where bottled LPG is often existing and used for cooking and heating. There is a high demand for electric power on yachts due to electric and electronic devices like refrigeration, lights, navigation and comfort equipment but a sufficient power supply is getting increasingly difficult. The nominal electric power output of the APU simulated as a device for recharging the battery was determined to be 300 W [1]. Advantageous specifications for a target product are low exhaust gas emission and fuel consumption leading to a high efficiency as well as marginal noise and vibration. The APU should be compact, lightweight and easy to handle and thus be equipped with an automatic control unit. Operation in extreme ambient conditions, e.g. a wide temperature range with temperature fluctuation, air contaminated with salt, varying inclination

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Nomenclature

FU	fuel utilisation of fuel cell
H_{low,H_2}	lower heat value (kJ kmol^{-1})

Greek letters

η	efficiency (%)
$\dot{n}_i$	mole flow (kmol s^{-1})

as well as vibrations has to be taken into account. Based on these product specifications a small-scale fuel processor for using LPG has been developed.

2. Description of the fuel processor

Transferring the target product specifications of the APU into the performance specifications for the fuel processor additional demands on the fuel processor development have been defined. The nominal hydrogen output of the fuel processor has been determined to 1 kW_{th,H_2} including a high hydrogen and low carbon monoxide content in the product gas. Short startup time and highly dynamic operation within a load range of 50–100% have to be achieved.

In order to realise the high hydrogen concentration in the product gas and the high efficiency of the fuel processor, the steam reforming (CSR) process combined with a catalytic burner (CB) and a water–gas shift (WGS) reactor downstream were chosen for the development [2,3]. The utilisation of the anode-offgas of the fuel cell in the catalytic burner is necessary for a high efficiency [4]. The WGS product gas contains about 1 mol% carbon monoxide. As PEM fuel cells operate at low temperature the carbon monoxide concentration has to be reduced to less than 50 ppm by a PrOx reactor.

2.1. Simulation

Basic thermodynamic simulations of the fuel processor in combination with the fuel cell were setup for a theoretical investigation of the system according to operation parameters, sensitivities and efficiency. The fuel cell had to be taken into account to investigate the influence of the anode-offgas which is used as fuel for the burner to partly substitute LPG [2]. The assumptions which were made for the basic simulation are shown in Table 1.

A characteristic diagram of the basic simulations is given in Fig. 1 for the CSR, WGS and PrOx output concentrations. For the steam reforming process, the concentrations of hydrogen, carbon monoxide, carbon dioxide, residual methane and water at thermodynamic equilibrium are charted. Methane is the only hydrocarbon being present at reformer temperatures above 500 °C. The output concentrations of the reformer are depending on the reaction temperature and the S/C ratio which is simulated to 2.8, 3 or 3.2, respectively (arrows in diagrams pointing towards higher S/C ratio) and the pressure which is set to 1 bar_{abs}. As there is no additional water feed acceptable downstream of the reforming zone the water–gas shift concentrations only depend on the shift reaction temperature. The concentration curves in the WGS diagram (Fig. 1) are determined for a reformer outlet temperature of 650 °C. This temperature is described in literature as reasonable according to a compromise between strain of material and catalyst and conversion rate [5]. The methane concentration is not presented in the WGS and PrOx diagram (Fig. 1) as the value is constant neglecting the side reactions in the basic simulation. The hydrogen, carbon dioxide and water output concentrations of the PrOx are simulated for 1 mol% carbon monoxide output concentration of the dry WGS product. These species are presented as points in the PrOx diagram (Fig. 1), because there is no thermodynamic temperature dependency. A fixed O/CO ratio of two and the complete conversion of oxygen with carbon monoxide and hydrogen are assumed, respectively.

Theoretically the highest efficiency of the fuel processor can be achieved at high reformer temperature and thermal integration of all released heat streams. Practically, maximal internal heat utilisation leads to complex design of the thermal management resulting in many dependent process variables [6]. Heat transfer and fluid dynamic resistances are obstacles for quick startup and variable load conditions. Nevertheless, fuel processors with focus on high heat integration have been developed but mostly in a power range above 3 kW_{th,H_2} for stationary applications [7] or up to 100 kW_{th,H_2} for propulsion applications [8].

Table 1
Assumptions for the basic thermodynamic simulation (concentrations in mol% of dry gas mixture, concentration of carbon monoxide after PrOx is assumed to 0 as approximation of 50 ppm for nearly complete conversion)

Specification	Assumption
Fuel	Propane (C_3H_8) as substitute for LPG
Steam to carbon ratio (S/C) of steam reformer	2.8–3.2
Product gas mixture of reformer/burner module	High hydrogen content, 300 °C
Reformate (product gas mixture of fuel processor)	Nominal hydrogen output = 1 kW_{th,H_2} (LHV), H_2 > 70 mol%, CO = 0 ppm, 80 °C
WGS	≤1 mol% CO, no additional quench water after reformer, no side reactions
PrOx	O/CO = 2, 0 ppm CO, complete conversion of oxygen by hydrogen, single stage
Pressure	Atmospheric pressure = 1 bar_{abs} without pressure drop
Fuel cell (PEMFC)	Fuel utilisation = 70%, efficiency = 50% (LHV)
Burner	Complete conversion of propane and anode-offgas
Anode-offgas of fuel cell	Full utilisation in the burner
Water	Closed water loop

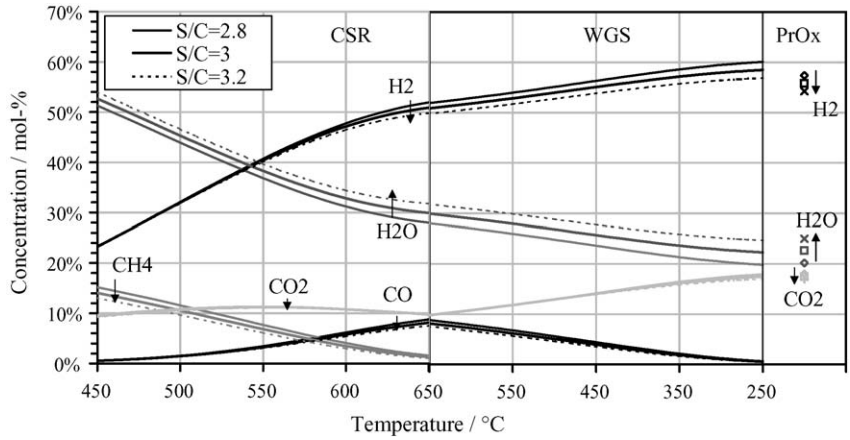

Fig. 1. Thermodynamic simulations: species output concentrations of CSR, WGS and PrOx with C_3H_8 input and S/C = 2.8, 3.0 and 3.2 at 1 bar_{abs}.

Further thermodynamic simulations were performed with fixed parameters (T_{Ref} = 650 °C, S/C = 3, T_{WGS} = 280 °C for 1 mol% CO at WGS outlet) to calculate the heat streams for evaluation of possible thermal integrations. The investigation resulted in a modular setup of the fuel processor consisting of a separate reformer/burner module and a CO-purification module (Fig. 2).

The heat integration within the reformer/burner module as high temperature module is essential for the efficiency increase. Heat streams of the CO-purification module are presented, which consist of the WGS process with 26 W, the intercooler between WGS and PrOx with 42 W resulting in 68 W as well as the PrOx reaction with 29 W and a second intercooler between the PrOx and the fuel cell with 4 W resulting in 33 W. The small values of the single heat streams lead to the conclusion that no further heat integration between the high and low temperature module is aimed. Therefore, the CO-purification module was planned with an independent cooling system separated from the reformer/burner module. Nevertheless, there are options for further heat integrations depending on the experimental results.

The efficiency of the fuel processor has been defined as

$$\eta = \frac{\dot{n}_{H_2,out} \cdot H_{low,H_2}}{\dot{n}_{C_3H_8,in} \cdot H_{low,C_3H_8}} \cdot FU. \quad (1)$$

The fuel utilisation (FU) of the fuel cell specifies the converted hydrogen in the fuel cell relating to the total hydrogen input of the fuel cell. Based on the simulations the theoretical efficiency of the fuel processor is 69.9% converting the anode-offgas in the burner, but without heat integration of the CO-purification module. A maximum theoretical efficiency of 74.4% could be achieved by using all possible heat streams. It can be concluded that the modular setup leads to a high but not maximum efficiency in terms of theoretical evaluation but with the practical advantages of a separate cooling system for the low temperature module, e.g. simplified system control. Additionally, the modular setup accelerates the reactor development, allows the easy replacement by an improved module and advances the potential for system scale.

Before the parallel reactor development started the interfaces between the reformer/burner and CO-purification, between the CO-purification and the fuel cell as well as between the fuel cell and the reformer/burner module were defined. The total mole flows, species concentrations and temperatures were calculated as relevant parameters for the module interfaces and therefore fixed as target values for the simultaneous module development.

2.2. Principle reactor design

The identified performing specifications of the fuel processor lead to principles for the reactor design. Precious metal catalysts were chosen because of high catalyst performance, no reduction process for commissioning and the non pyrophoric behaviour in oxidizing atmosphere [9]. The catalysts are coated on monolithic supports which show high stability in rough conditions as well as high heat transfer and low thermal inertia when using metallic supports [10]. Catalysts for CSR, CB, WGS and PrOx supplied by different catalyst manufacturers were screened

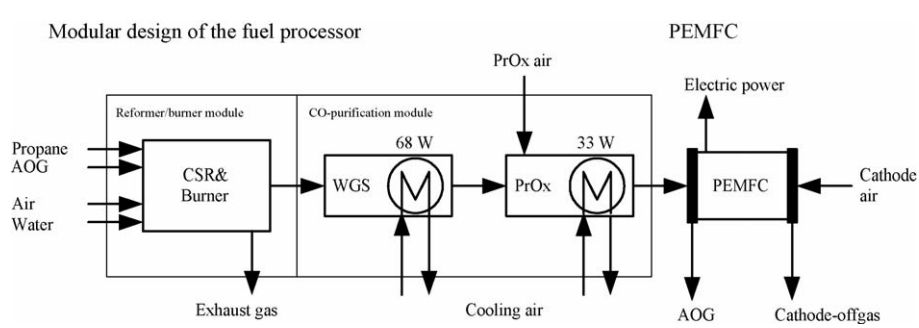

Fig. 2. Modular setup of fuel processor with heat streams of the CO-purification module.

for benchmarking and selection. The selected catalysts were extensively characterised in screening and kinetic experiments as basis for the reactor development. General norms for small reactor design were applied, e.g. low thermal inertia, high heat transfer where necessary, excellent insulation, optimisation of fluid flow and pressure drop as well as appropriate materials, semi-finished products and low cost manufacturing. Additionally, a multiplicity of sensors like thermocouples, fittings for pressure sensors and gas sampling were integrated into the reactors and heat exchangers for experimental characterisation of the system. The simulations to support the design process of the reactors were performed with ChemCAD® for thermodynamic examination and Fluent® for optimising the fluid mechanics.

2.3. Reformer/burner module

The reformer/burner module includes the steam reforming zone, the catalytic burner, the water evaporator and several heat exchangers. Input streams of LPG, liquid water and air as well as the anode-offgas are heated up by cooling down the exhaust gas and reformate employing internal heat exchangers. The required heat for the reforming process is provided by the oxidation of LPG and anode-offgas in the catalytic burner. Catalytic combustion offers several advantages over conventional flame combustion, e.g. low peak temperatures, low emission levels in the exhaust gas, high fuel tolerance and high fuel utilisation [11,12]. In order to increase the process efficiency the burner is operated with the anode-offgas of the fuel cell and LPG in addition. Due to the strongly exothermic oxidation reaction of hydrogen, propane and methane and the high heat conductivity of the metallic structure the gas hourly space velocity (GHSV) of 15,000 h^{-1} could be applied for the reformer at nominal load. The burner catalyst was designed with a GHSV of 60,000 h^{-1} ensuring a complete conversion of hydrocarbons and hydrogen. An equilibrium composition at 650 °C reformer outlet temperature, a product gas temperature of 300 °C and an exhaust gas temperature of 100 °C were aimed.

2.4. CO-purification module

The CO-purification module is consisting of two adiabatic WGS reactors and a single-stage PrOx reactor with an integrated heat exchanger. There are two more heat exchangers implemented between the WGS reactors as well as between the second WGS and PrOx reactor to adjust the input temperatures of the reactors.

The high CO-concentration of around 12 mol% at the outlet of the reformer/burner module has to be reduced to about 1 mol% at an equilibrium temperature of around 280 °C at WGS outlet. The tests of different WGS catalysts lead to the conclusion that two adiabatic reactors based on a medium temperature catalyst (MTS) with a GHSV of 20,000 h^{-1} and a low temperature catalyst (LTS) with a GHSV of 10,000 h^{-1} are suitable for the fuel processor setup. Because of the adiabatic design and the minimisation of axial and radial temperature gradients the precious metal catalysts were coated on ceramic monoliths. The thermodynamic simulations determine temperature increases of 68 K in the MTS and 15 K in the LTS reactor assuming a perfectly adiabatic system. The output concentrations of the two reactors depend only on the input temperatures and composition of the input gas mixture. Precise design of the heat exchangers is essential for the entire load range to control the reactors.

For the fuel processor the target output CO-concentration was fixed to less than 50 ppm for steady state and dynamic operation. Within the interface of the WGS and PrOx the dry carbon monoxide input concentration was defined to 1 mol%. The PrOx reaction is known to be a selectivity sensitive reaction with competing kinetics of carbon monoxide and hydrogen oxidation as well as reverse WGS reaction depending on local temperatures inside the reactor [13]. Therefore, the single-stage PrOx reactor is designed as a temperature controlled reactor on the basis of metallic structures to optimise the heat transfer from the exothermic reaction to the cooling fluid. The PrOx reactor consists of a mixing zone where air is fed to the process gas, the reaction zone and the internal heat exchanger. The metal monolith was coated with the precious metal PrOx catalyst designed for a GHSV of 15,000 h^{-1}.

3. Experimental investigation

To date more than 500 h operation time has been achieved to characterise and optimise the total fuel processor in the laboratory test stand. Within this time a multitude of test procedures have been run, e.g. startup and shutdown cycles, steady state and dynamic operation, to evaluate the performance of the fuel processor and indicate the weak points for further optimisation steps. For detailed analysis several sampling points, pressure sensors and thermocouples have been integrated into the system. Commercial bottles of propane (DIN 51 622) have been used for the experimental investigations, because of the undefined and varying gas composition of LPG cylinders. All media were regulated by mass flow controllers (MFC). A desulphurisation unit filled with activated carbon was placed upstream of the propane MFCs. The test stand is equipped with the software package LabVIEW® for data acquisition and control.

While first test series were operated manually, automation for startup, steady state and dynamic operation has been implemented for the following test phases. For each load the volume flows of all species have been defined and implemented as parameter sets in LabVIEW®. Switching between these parameter sets can be carried out directly or by a ramp function using the reformer propane flow as reference value.

3.1. Startup

During cold startup the burner feed is a mixture of propane, all species of a synthetic anode-offgas and air. The catalytic oxidation of hydrogen as component of the gas mixture starts the burner at ambient temperature without additional ignition energy. The composition of the synthetic anode-offgas is calculated with the fuel processor reformate according to the above mentioned simulation and the assumption of 70% fuel utilisation in the fuel cell. Air is added with high stoichiometric air ratios between 1.43 and 1.7. The stoichiometric air ratio is defined as

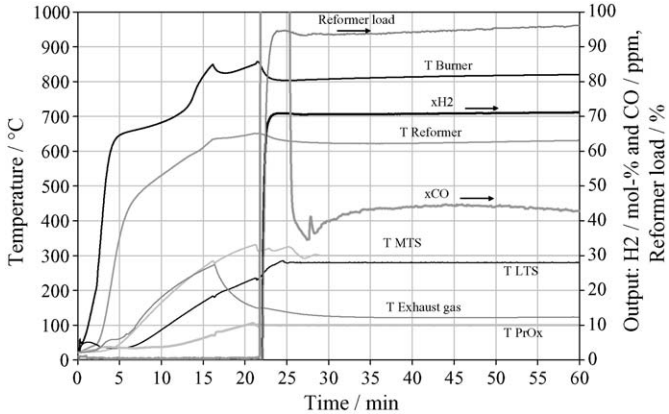

Fig. 3. Cold startup of fuel processor.

applied air flow relating to the required air flow for complete conversion. The excessive nitrogen and oxygen content prevent high temperature gradients in the burner due to the heat capacities. Hence, the air flow can be used as a control mechanism.

For the cold startup procedure characteristic temperatures of the reformer, burner, the two WGS reactors and the PrOx reactor as well as hydrogen and carbon monoxide concentrations at the fuel processor outlet are shown in Fig. 3. The startup procedure can be divided into four phases. In the first phase the fuel processor is heated up with 50% burner load. The load percentage of the burner is related to the burner power at nominal fuel processor output of 1 kW_{th,H_2}. After 2 min the second phase continues with 100% burner load. During these two phases air is used as feed for the reformer process in order to distribute the generated heat of the burner into the reforming zone and the consecutive WGS and PrOx reactors. After 16 min the burner load is changed to 75% with a reduced stoichiometric air ratio of 1.43 and the reformer feed is switched from pure air to a water and air mixture. In this third phase the exhaust gas is cooled down by evaporating the water and heating up the complete feed. In the fourth phase after further 5 min the burner is operated at 100% load again and the reformer process is fed with propane and water according to 100% reformer load. As shown in Fig. 3 hydrogen is produced immediately and the reformer load which is equivalent to the hydrogen power output of the fuel processor is continuously increasing according to rising reformer temperatures.

During the first three startup phases the MTS, LTS and PrOx reactors are heated up by the air and air–water mixture. In phase four the inlet temperatures of the MTS and PrOx reactors are controlled by air-cooled heat exchangers regulated via PID controllers. Within 1 min after starting phase four the dry gas concentration of hydrogen at the fuel processor outlet reaches about 71 mol%. By an additional air flow at the inlet of the LTS reactor the temperatures are increased into the active range of the LTS catalyst. Thus, 25 min after startup about 100% load is achieved and the carbon monoxide concentration is reduced to around 1 mol% at the LTS outlet and below 50 ppm at fuel process outlet, respectively.

The cold startup of the burner by internal ignition of LPG is currently tested and will be integrated into the next fuel processor generation.

3.2. Steady state and dynamic operation

Dynamic and steady state operation have been tested in the load range between 50 and 120%, where 100% represents 1 kW_{th,H_2}. Therefore, 50, 75, 100 and 120% load increments have been defined as discrete load levels. The propane flows to the burner and the reformer, the S/C ratios and the stoichiometric air ratios of the burner and the PrOx reactor have been determined by simulations and the single module characterisations. The corresponding values are shown in Table 2 for the four load levels and were implemented as parameter sets in the control software.

During operation the propane flows to the burner and reformer are set according to Table 2 and the reformer water flow is calculated according to the S/C ratio. The air flow rate to the PrOx reactor is continuously calculated with the input values of the reformer shown in Table 2 and the measured CO-concentration at the outlet of the LTS reactor. The anode-offgas composition is continuously calculated with the measured reformate gas composition at the outlet of the LTS reactor, the reformer propane and water flow and the PrOx air flow and assuming the 70% fuel utilisation in a fuel cell, respectively. Also the corresponding burner air flow rate is calculated with the burner lambda and the anode-offgas composition.

Fig. 4 depicts the measured values for the hydrogen and carbon monoxide output concentrations, the propane mass flow and the pressure drop as well as the calculated efficiency for increasing and decreasing load in the range of 50–120%. Fast transient responses of the fuel processor with negligible fluctuation of reformate gas composition within the load variations can be measured. These fluctuations are explained by varying S/C ratios and reactor temperature profiles. The load curve represents the total flow rate of hydrogen which is calculated with the measured product gas composition and the input volume flows of propane, water and PrOx–air. During dynamic and steady state operation the CO-concentration is constantly below 50 ppm. As load

Table 2
Input values for the defined parameter sets of the load levels

Load (%)	Reformer		Burner		PrOx
	C_3H_8 (sl min^{-1})	S/C	C_3H_8 (sl min^{-1})	Lambda	O/CO
50	0.312	3.2	0.087	1.35	1.8
75	0.464	3.0	0.106	1.43	1.8
100	0.619	3.1	0.135	1.43	1.9
120	0.744	3.2	0.151	1.43	1.9

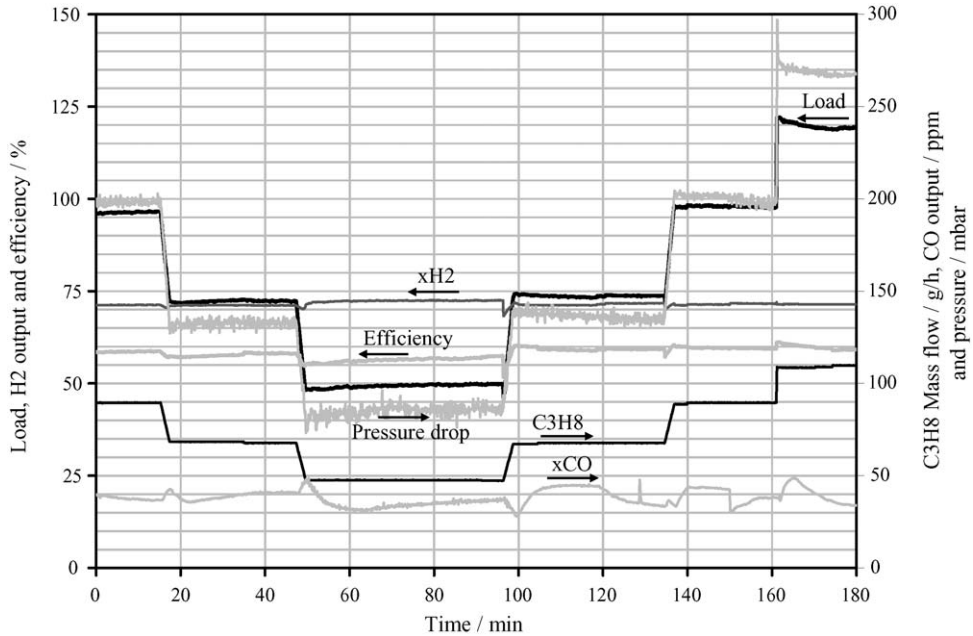

Fig. 4. Dynamic and steady state performance of fuel processor.

reduction leads to short-term temperature drop in the reformer the reformate flow rate decreases and a lower efficiency of the gas process is calculated as burner operation remains constant. Increasing load generates a contrary system performance.

The time period of 90 s per 25% load change is based on the alteration speed of the reference value (reformer propane) for the ramp function. Due to the different performances of the MFCs the load change velocity is limited, because a rapid load variation leads to overshooting and therefore instable flows. To visualise this effect the load change from 100 to 120% as shown in Fig. 4 is operated directly without ramp function. A high overflow of the water results in a pressure peak of about 25 mbar. Due to the sensitivity of the CO-purification module according to the partial pressure of water fluctuations can result in CO peaks at fuel processor outlet. Hence, load change time cannot be reduced while operating with MFCs.

The fuel processor efficiency according to Eq. (1) is between 56 and 60% in the complete load range. The maximum theoretical efficiency for the current system as described in Section 2.1 is about 70%. The difference can be explained by thermal losses due to the insulation, a large number of fittings for sensors and the exhaust gas temperature of about 130 °C instead of 100 °C as well as an additional air-cooled heat exchanger between the reformer/burner and the CO-purification module. Obviously heat loss effects have a large impact on the efficiency in small-scale reformer systems.

4. Packaging

A compact reformer/burner module and CO-purification module have been designed and experimentally investigated. As depicted in Fig. 5a from left to right the reformer/burner module has been assembled as single component enclosed with high performance insulation material, the WGS reactors with the heat exchangers are the second and the PrOx reactor the third component. For the first coupling of the fuel processor these separately insulated components were simply connected with fittings in serial without optimising the configuration of the reactors, heat exchangers, piping and insulation. This arrangement was the basis for the experimental investigations presented in this paper.

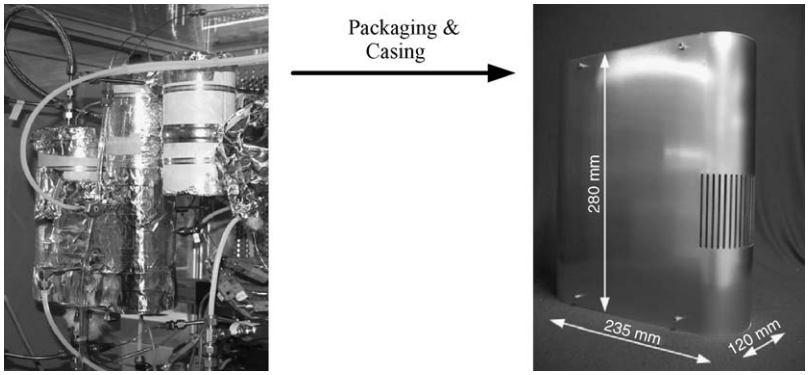

Fig. 5. (a) Current fuel processor in the laboratory test stand and (b) casing for the packaging concept of the current fuel processor.

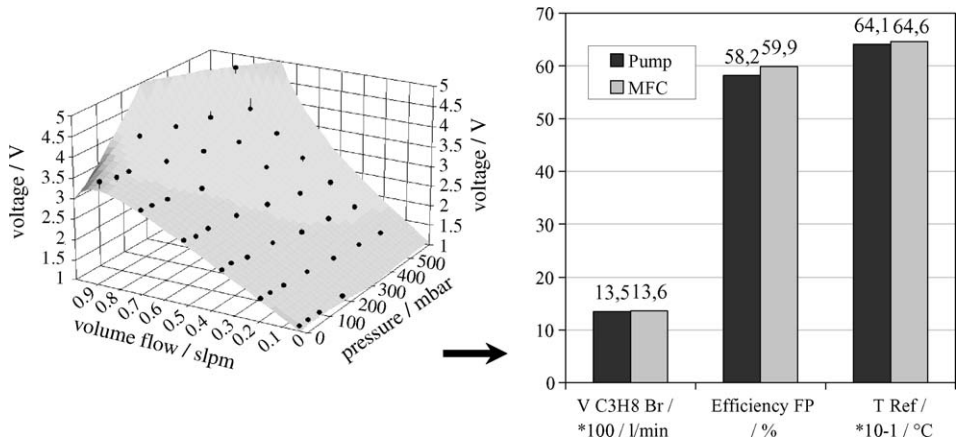

Fig. 6. Exemplary data of a tested pump for the burner propane.

The dimensions of this setup are resulting in a volume of about 17 l with a weight of 3.6 kg. The size and weight of the reactors and heat exchangers are 0.74 l and 1.6 kg which demonstrates the potential in size and weight reduction of the fuel processor.

Concepts for the configuration of the fuel processor components have been developed to increase the volumetric and gravimetric power density. The insulation plays a key role in size and weight issues but was not significantly changed in the first packaging concept. This allows further volume and weight reduction for future system packaging. In Fig. 5b, the casing and dimensions are depicted for the first packaging of the current fuel processor without changing the reactors and heat exchangers itself but their arrangement by an optimised piping. The volume can be reduced by factor 2.5 to about 7 l and the weight to 3 kg. The associated volumetric and gravimetric power densities are 143 $W_{th}\,l^{-1}$ and 333 $W_{th}\,kg^{-1}$ relating to the thermal hydrogen output of the fuel processor. This fuel processor is currently under construction.

5. Peripheral components

Beside the experimental investigations of the fuel processor the transfer to an autonomous system is a major topic. Substitution of complete laboratory equipment by peripheral components has to be realised. Thus, performance specifications for necessary components were defined by detailed system analysis in a specification sheet. Based on this specification sheet a first selection of components, e.g. pumps, valves and heat exchangers has been tested, integrated and evaluated according to the performance of the fuel processor.

A methodical procedure has been developed for the integration of peripheral components into the fuel processor:

I. Definition of component specification.
II. Determination of the characteristic diagram by tests in a component test stand.
III. Transformation of the results into a mathematical function.
IV. Component integration into the fuel processor test stand.
V. Automated operation of the fuel processor with singular component.
VI. Modification of the mathematical function considering the operation under real conditions.
VII. Component evaluation according to fuel processor test results.

In Fig. 6, two diagrams describing the methodical procedure for the integration of the burner propane pump are presented. The mathematical function is generated with the software TableCurve3D® by implementing the measured data. The resulting function calculates a discrete value as control voltage depending on the desired volume flow and the measured outlet pressure considering the inlet pressure as atmospheric.

For system test the pump had to be integrated into the laboratory test stand and the mathematical function implemented into the software, respectively. During startup and steady state operation no fluctuations have been measured. At nominal load the negative deviation of the propane flow rate generated by the pump is about 1% resulting in a lower reformer outlet temperature and therefore in an efficiency reduction.

Beside the burner propane pump further components (reformer propane and water pump, anode-offgas pump and heat exchangers) were tested and evaluated. The evaluation of the water pump showed that further detailed tests in the separate test rig have to be made. The anode-offgas recirculation and the closed water cycle are designed and will be tested in the next test series as well as the air pumps for the burner, LTS and PrOx reactors.

6. Summary and outlook

The Centre for Fuel Cell Technology is currently developing a fuel cell APU based on a fuel processor using LPG and a PEM fuel cell. The compact fuel processor consists of the reformer/burner module and the CO-purification module, employing water–gas shift and single-stage preferential oxidation reactors. High performance precious metal catalysts on monolithic supports are chosen for all process stages. The

nominal hydrogen power output is $1\,kW_{th,H_2}$. Automated steady state and dynamic operation have been demonstrated within a load range of 50–120% running the fuel processor with commercial propane. Also during dynamic operation and part load the product concentrations show very low fluctuations as well as carbon monoxide is constantly under-running the 50 ppm limit. Hence, the fuel processor is suitable for coupling with the PEM fuel cell. First concepts for packaging have been developed resulting in a compact and lightweight fuel processor with 7 l volume and 3 kg weight including the insulation. For an autonomous operation of the fuel processor the specification list for peripheral components was compiled and first tests of selected commercial components were performed. The fuel processor has been partly investigated with peripheral components.

The further developments include startup with LPG, minimisation of startup time, maximisation of efficiency and reduction of weight and volume. Long-term testing in an automated test stand including realistic test cycles has to be performed to demonstrate the stability of the fuel processor and the catalysts. Derived from the component tests there is the need for adapting and improving the peripheral components in order to fit the specific demands. Stepwise integration is continued and the control for a complete automation has to be developed.

Acknowledgements

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