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Compact gasoline fuel processor for passenger vehicle APU

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Abstract

Due to the increasing demand for electrical power in today's passenger vehicles, and with the requirements regarding fuel consumption and environmental sustainability tightening, a fuel cell-based auxiliary power unit (APU) becomes a promising alternative to the conventional generation of electrical energy via internal combustion engine, generator and battery. It is obvious that the on-board stored fuel has to be used for the fuel cell system, thus, gasoline or diesel has to be reformed on board. This makes the auxiliary power unit a complex integrated system of stack, air supply, fuel processor, electrics as well as heat and water management. Aside from proving the technical feasibility of such a system, the development has to address three major barriers:start-up time, costs, and size/weight of the systems. In this paper a packaging concept for an auxiliary power unit is presented. The main emphasis is placed on the fuel processor, as good packaging of this large subsystem has the strongest impact on overall size.

The fuel processor system consists of an autothermal reformer in combination with water–gas shift and selective oxidation stages, based on adiabatic reactors with inter-cooling. The configuration was realized in a laboratory set-up and experimentally investigated. The results gained from this confirm a general suitability for mobile applications. A start-up time of 30 min was measured, while a potential reduction to 10 min seems feasible. An overall fuel processor efficiency of about 77% was measured. On the basis of the know-how gained by the experimental investigation of the laboratory set-up a packaging concept was developed. Using state-of-the-art catalyst and heat exchanger technology, the volumes of these components are fixed. However, the overall volume is higher mainly due to mixing zones and flow ducts, which do not contribute to the chemical or thermal function of the system. Thus, the concept developed mainly focuses on minimization of those component volumes. Therefore, the packaging utilizes rectangular catalyst bricks and integrates flow ducts into the heat exchangers. A concept is presented with a 25 l fuel processor volume including thermal isolation for a 3 kW_{el} auxiliary power unit. The overall size of the system, i.e. including stack, air supply and auxiliaries can be estimated to 44 l.

Keywords: Fuel processing; Reforming; Auxiliary power unit

1. Introduction

Depending on the vehicle class and its equipment, electrical power consumption of today's passenger vehicles ranges from 1 to 5 kW_{el}. It is obvious, that the demand of electrical power will increase even more in the future, due to the introduction of new electrical and mechatronical systems, which contribute to vehicle comfort (e.g. electrical mirror heating, seat regulation) or to its safety (e.g. electronic stability program, steer-by-wire, brake-by-wire). Furthermore a lot of auxiliary systems of the internal combustion engine can be powered by electric motors instead of the mechanical connection to the crankshaft. This enables an energy saving operation independently from the engine or it may improve the engine performance, e.g. with electromechanical valve trains. This requires a high power, highly efficient generation of electricity in the vehicle. A fuel cell-based auxiliary

Abbreviations: APU, auxiliary power unit; ATR, autothermal reformer; CB, catalytic burner; CPO, catalytic partial oxidation; LTS, low temperature water–gas shift; HEX, heat exchanger; HTS, high temperature water–gas shift; PEM, proton exchange membrane; SelOx, selective oxidation; SOFC, solide oxide fuel cell

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Nomenclature

H_m	molar lower calorific value
η	efficiency
$\dot{n}_i$	molar flow

power unit (APU) can be designed for much higher power outputs with a much higher efficiency compared to the conventional electrical power generation in today's internal combustion engines via engine and generator. Aside from the benefit due to lower fuel consumption and carbon dioxide emissions such systems can feature several advantages. Being independent from engine operation, electrical energy is available any time, even when the engine is turned of. This enables air conditioning before entering the vehicle as well as the operation of recreational devices at any time. The system can also be used to supply power to external consumers, e.g. trailers.

It is obvious, that the auxiliary power unit has to be supplied with the fuel stored on-board, such as gasoline or diesel. The fuel cell system then is consisting of the following subsystems. The fuel cell stack, which generates the electrical power from oxygen and hydrogen, a fuel processor for hydrogen generation, an air supply system as well as some auxiliaries, e.g. pumps and cooling devices.

Several APU concepts have been proposed, some prove of concept demonstrators have been presented and only few systems are commercially available. None of the latter is fuelled by gasoline or diesel. Last but not least, this is due to the fact, that it is very challenging to design the fuel processors in a reasonable size. In this paper, the development of a packaging concept for a gasoline fuel processor is presented. As no detailed geometry data for such a system is available from literature, first an experimental prototype had to be set up in order to collect the required geometry data.

2. Review of recent fuel cell auxiliary power unit development

Several fuel cell-based APU concepts have been proposed and some demonstrators have been built up for various applications, particularly passenger cars, heavy trucks or recreational vehicles. In the following a brief review of recent APU developments is given, with special focus on the power density of their fuel supply or fuel processing system.

Ballard in cooperation with Freightliner has demonstrated a PEM fuel cell APU on a Freightliner truck [1]. The APU has an output of 1.4 kW of power, either on a 120 VAC or 12 VDC level. Hydrogen is stored on board the vehicle in a 200 l pressure vessel at 170 bar. It can be fed to the fuel cell without further refining, which makes the anode fuel supply system comparably simple.

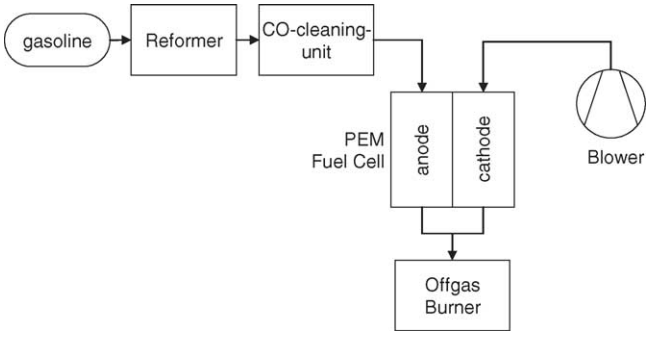

Fig. 1. Gasoline fuelled auxiliary power unit.

Among the first fuel cell products, available to private customers, smart fuel cell will begin to sell the direct methanol fuel cell (DMFC) APU SFC A50. The system delivers 50 W at 12VDC for different purposes, e.g. to power recreational devices. The system is directly supplied by methanol, so no fuel processing is required. Standard sizes of methanol tanks are 5 and 10 l. The methanol consumption amounts to 1.3 l kWh^{-1} [2].

Delphi automotive systems has developed a gasoline fuelled APU on base of a solid oxide fuel cell stack (SOFC) [3]. In passenger vehicles, it is intended to supply energy to the vehicles electrical system and to power an air conditioning unit. At the current stage of development the system has an output of around 2 kW. The overall size of the system amounts to approximately 60 l. In a reformer, gasoline is converted to a synthesis gas mainly consisting of hydrogen, carbon monoxide, carbon dioxide, nitrogen, and water. This gas can directly be supplied to the fuel cell anode, where an electrochemical reaction converts carbon monoxide analogue to hydrogen producing electricity. The overall system is comparably compact, featuring a power density of >33 W l^{-1}.

Also APU concepts have been presented, that combine a PEM fuel cell with a fuel processor, enabling the use of a variety of hydrocarbons instead of hydrogen (Fig. 1). Contrary to the SOFC the PEM requires a carbon monoxide free anode gas supply. Hence, the fuel processors are rather complex, because aside from the reformer a carbon monoxide cleaning unit has to be integrated. Such fuel processors have been developed to convert gasoline in automotive fuel cell propulsion systems, mostly based on autothermal reforming [4]. In comparison to APU applications these systems have a much higher power output ranging above 50 kW and reach much higher power densities.

IdaTech has demonstrated a gasoline fueled APU as a portable power generator with a 1 kW power output [5]. In the system a steam reformer is combined with a hydrogen permeable separation membrane, producing hydrogen for a "Nexa power module" from Ballard. The unit can be used for different purposes, e.g. military or recreational applications. The overall volume of the system amounts to approximately 220 l showing a power density around 5 W l^{-1}. The fuel pro-

cessor's volume can be estimated to be around one half of the total system volume.

There are also some analogies between fuel cell APU systems and PEM fuel cells, which are used in combined heat and power generation plants for domestic applications. Typically these systems are fuelled with natural gas and use a steam reformer in combination with a CO-cleanup-unit to generate the required hydrogen. As these systems have fewer restrictions concerning their size, their power density is much lower compared to portable or mobile applications.

Among other drawbacks, the large system size of gasoline fuelled PEM APU concepts is one reason why no automotive product has been presented yet. No laboratory set-up or proof of concept demonstrator has been published, that achieves the same power density as the Delphi SOFC based APU concept. Therefore, the potential of a gasoline fuelled PEM APU might be strongly dependent on the improvement of power densities. As the gasoline fuel processor usually is the largest subsystem, occupying around half of the overall volume, it is most effective to reduce system size by improving the compactness of the fuel processor. In this paper a new packaging concept for such a fuel processor is presented.

3. Experimental set-up

The design of a fuel processor packaging concept has to be based on a validated system structure and valid data for component geometry. Today no detailed data of gasoline fuel processors for automotive PEM APU concepts are published. Therefore, a fuel processor system was designed, set up and tested, in order to deliver the required data. Fig. 2 shows the flow diagram of the experimental set-up. Fuel is injected into a mixing chamber, where preheated air and steam is added. These reactants are converted to a hydrogen rich, carbon monoxide containing synthesis gas in an autothermal reformer. The carbon monoxide content is subsequently reduced in two water–gas-shift stages, up to a rest content of <1%. By the addition of air a further reduction of the carbon monoxide content takes place in a selective oxidation. For the experiments no fuel cell was used, thus, the complete synthesis gas was converted in an offgas burner.

The operating temperatures of this series of reactor stages is falling from around 700 °C in the reformer, over 400–500 °C in the high temperature shift to 250–320 °C in the low temperature shift and selective oxidation to 80 °C at the burner inlet. The inlet temperatures are controlled by intercoolers, which are used to generate steam and preheat air for the autothermal reformer. Therefore, cold air is being supplied to the coldest heat exchanger and then passed to the other components in the order of increasing temperature, subsequently being preheated. All components are equipped with an injection valve to meter the water for steam generation and at the same time to control the synthesis gas temperature downstream.

The system was mounted on a test bench with adequate infrastructure for fuel, water, and air supply. While fuel and water is supplied by automotive applicable pumps, air supply is measured by mass flow controllers. The system was fitted with temperature sensors and gas suction probes downstream each reactor for gas analysis. Fig. 3 shows a picture of the set-up.

As a part of the fuel processor design a control strategy was developed. A detailed description of the control system architecture can be found in [6]. The control system was operated with the rapid prototype controller system XPC-target from

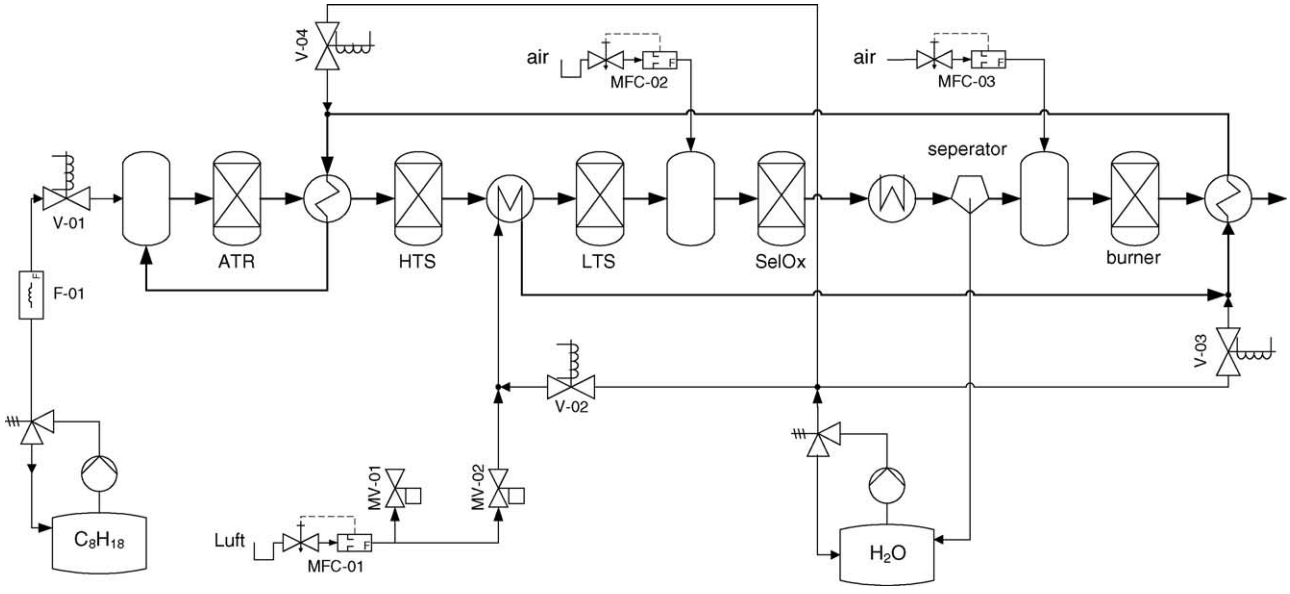

Fig. 2. Flow diagram of experimental set-up.

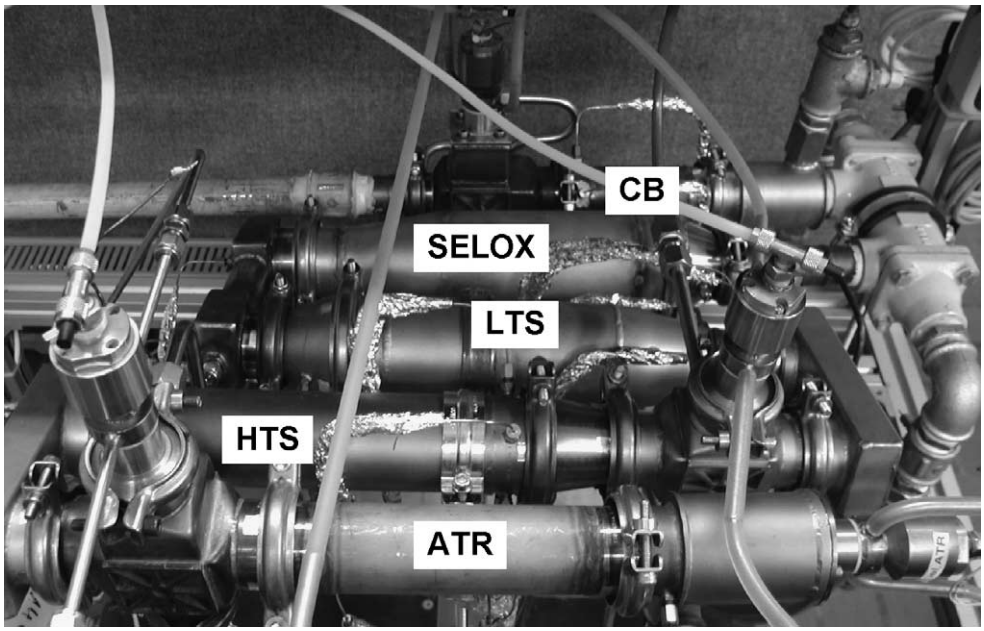

Fig. 3. Fuel processor experimental prototype.

The Mathworks®. This platform allows the realization of fast closed loop control cycles as well as the implementation of a state machine to actuate subsequential control actions (e.g. start-up procedure) using the toolbox Stateflow®.

4. Results of experimental prototype

The experimental prototype was operated under steady state conditions as well as transient in a power range of 3–9 kW thermal power, corresponding to around 1–3 kW electrical fuel cell power.

4.1. Steady-state performance

Due to its high temperatures between 600 and 800 °C the autothermal reformer is operating very close to chemical equilibrium. Depending on the rel. air–fuel-ratio and the steam-to-carbon-ratio, hydrogen contents between 32 and 42% are reached (Fig. 4). The efficiency of the reformer can be defined by the assumption, that the carbon monoxide flow will be converted to hydrogen in the following water–gas shift stages [7].

$$\eta = \frac{(\dot{n}_{H_2} + \dot{n}_{CO}) H_{mH_2}}{\dot{n}_{Fuel}\, H_{mFuel}}.$$

In this definition, the efficiency is independent from the water–gas shift-equilibrium and thus nearly not influenced by the amount of water supplied. However, it is strongly influenced by the rel. air–fuel-ratio. An optimum is reached, when enough oxidant is available for sufficient hydrocarbon conversion, but the products hydrogen and carbon monoxide are unburned. The temperatures, which are required for decomposition of the hydrocarbons, are reached by the exothermal reaction of the supplied oxygen. If the inlet temperature of the process is higher, less oxygen has to be supplied to reach these temperatures and less hydrogen and carbon monoxide will be burned. The optimal air–fuel-ratio decreases, while gaining maximum efficiency. This effect can also be seen in Fig. 5, because the inlet temperature was increasing together with the steam-to-carbon-ratio during the experiment.

As shown in Fig. 4 the system is using a two stage water–gas-shift reaction to convert the CO content in the reformer synthesis gas from around 10 to <1%. In the first stage around 60% CO is converted at temperatures between 4500 and 500 °C and in the second stage 80% CO conversion is achieved around temperatures of 270 °C (Fig. 6). At lower temperatures the conversion is kinetically limited. Increasing temperature in this region accelerates the reactions, causing a higher conversion rate and the process is moving

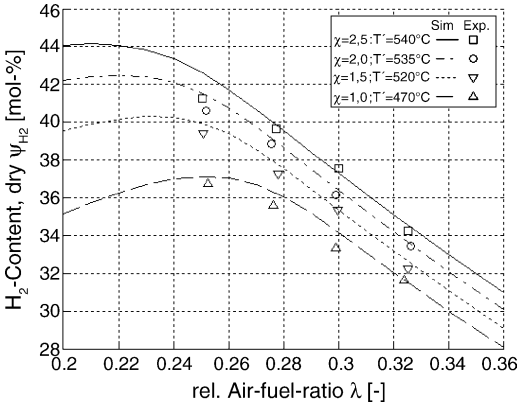

Fig. 4. H_2-concentration of autothermal reformer synthesis gas.

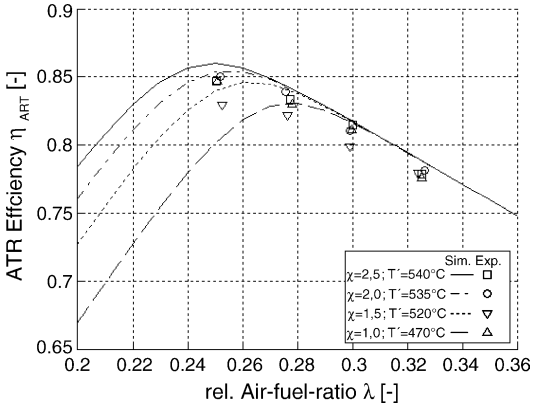

Fig. 5. Efficiency of autothermal reformer.

closer towards equilibrium. Because of the exothermal reaction, a further temperature rise will move the equilibrium backwards to the feed composition and CO conversion drops again.

The concept of water injection into the heat exchangers allows controlling of the reactor inlet temperatures, so that both stages can be operated to their optimal point. Due to the lower space velocity at partial load, the optimal CO conversion temperature decreases, while maximum conversion is increasing. However, here the share of thermal losses compared to the overall power increases, and less steam can be evaporated at steady state conditions. Thus, the optimal conversion temperature is decreasing, but only a slight gain of conversion rate in the high temperature stage and even a conversion loss in the low temperature stage occurs at part load.

Figs. 7 and 8 summarize the overall process for a thermal power of 9 kW in a temperature–concentration-plot. The horizontal lines indicate inter cooling, while the steep lines show the different reaction stages. Again it can be seen, that the reformer as well as the shift stages are operating close to equilibrium. While these reactors perform like they were designed, the selective oxidation shows insufficient conversion. The best point obtained is shown in Fig. 7 at an outlet concentration of 160 ppm, while 100 ppm is required.

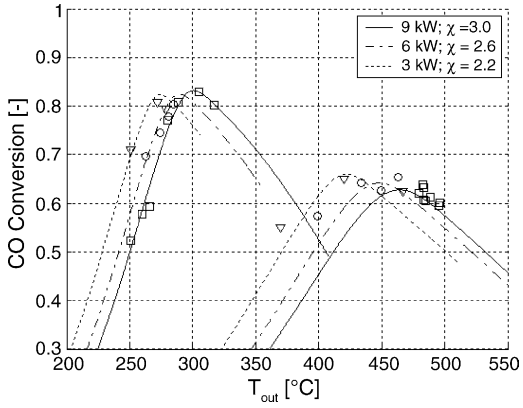

Fig. 6. CO conversion in water–gas-shift reactors.

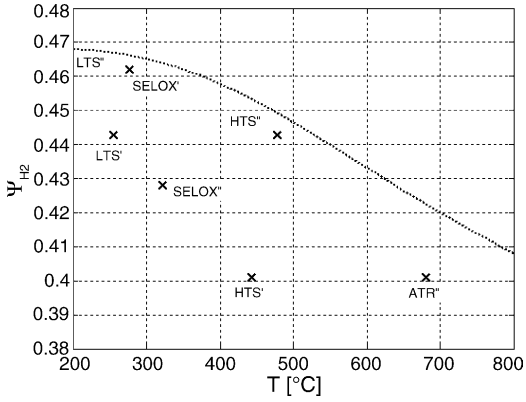

Fig. 7. H_2-concentration–temperature-plot of fuel processor.

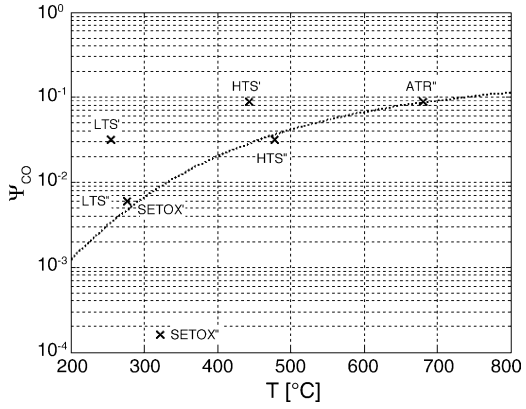

Fig. 8. CO-concentration–temperature-plot of the fuel processor.

4.2. Transient performance

Fig. 9 shows the start-up procedure of the experimental prototype. First the reformer is preheated by supplying hot air. Once its light off temperature is reached, fuel is injected and the catalytic partial oxidation starts immediately. The produced synthesis gas is lead through the system and finally is converted in the catalytic burner. The different heat exchangers are heated by the hot synthesis gas and the burner exhaust gas. Water can be injected and as the system heats up, the total steam-to-carbon-ratio is increased, while the rel.

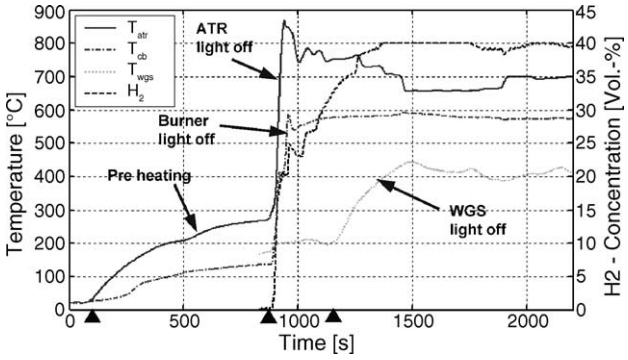

Fig. 9. Start-up of fuel processor.

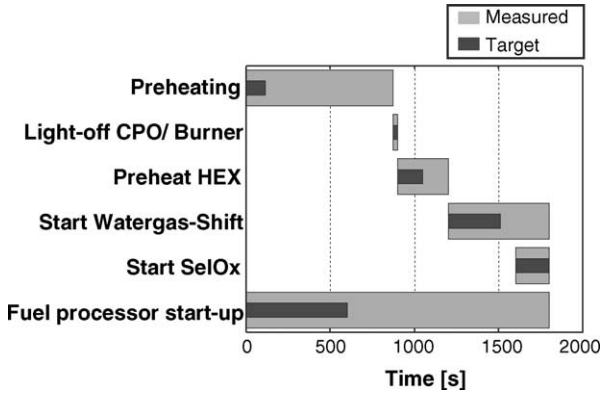

Fig. 10. Duration of start-up phases.

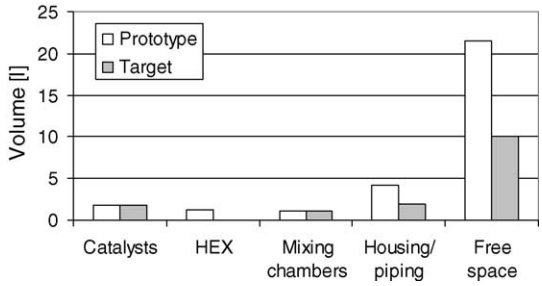

Fig. 11. Volume contribution of fuel processor.

air–fuel-ratio can be decreased. The water–gas-shift reactors light-off when both, inlet temperature and amount of available steam are high enough. Finally, the selective oxidation can be started by supplying air. Even if the CO inlet concentration is still too high compared to final steady-state operation, the selective oxidation can be started by addition of an understoichiometric air flow. Thus, heating up of both reactors, selective oxidation and low temperature shift, can occur in parallel.

Fig. 10 shows the different time spans that are required for each step of the start procedure. Especially the preheating phase of the system has to be strongly shortened, as this period significantly contributes to the overall start-up time. The main measure to reduce start-up time is to decrease thermal capacity of the system. The experimental prototype has a weight of around 18 kg, while the packaging concept presented below has a projected mass of 6.5 kg. This means a reduction of thermal capacity to nearly a third. The preheating time additionally can be shortened by concentrating the preheating energy on the catalyst brick of the autothermal reformer. In the experimental prototype the air supplied to the mixing chamber of the reformer was heated with 800 W electrical power and around 750 s were required to reach light-off temperature. By recuperation of a part of the electrical heat using a heat exchanger downstream the reformer, this phase was shortened to 500 s. Using an additional 800 W heating device to create a hot spot on the catalyst reduced the start-up time further more to 100 s. Even if the power was doubled for this set-up, the introduced energy was reduced from 600 to 160 kJ. Assuming a reduction of the heat up time of heat exchangers and water–gas-shift reactors by 50% due to the lower thermal capacity of the system, the overall start-up time can be shortened from 30 to less than 10 min.

4.3. Relevant data for packaging concept

The experimental investigation of the fuel processing concept has proven the basic functionality in steady-state as well as transient performance. Hence, the geometry of the different components can be used as a valid data basis for the development of a packaging concept. Table 1 gives an overview about the collected data.

5. Packaging concept

Reasonable system size is one of the most crucial barriers for mobile application of fuel cell systems. The experimental prototype has a volume of 40 l (w/o isolation) and is much too large for a passenger vehicle. It was analyzed which volumes are shared by the different types of components (Fig. 11). The functional components, i.e. catalysts, reactors and mixing chambers, only contribute a minor amount to overall system size. Significantly larger space is required by housings and piping, which are required to connect the components and

Table 1
Geometry data for packaging concept

Component	Dimensions (mm)	Volume (dm^3)	Surface area (m^2)
ATR catalyst	Ø = 40; L = 80	0.1	0.33
HTS catalyst	Ø = 52; L = 105	0.22	0.72
LTS catalyst	Ø = 72; L = 145	0.6	1.91
SelOx catalyst	Ø = 80; L = 120	0.6	1.95
Burner catalyst	Ø = 58; L = 116	0.31	0.99
HEX ATR-HTS	50 × 50 × 50	0.13	0.12
HEX HTS-LTS	50 × 50 × 50	0.13	0.12
HEX SelOx-CB	50 × 50 × 50	0.13	0.12
HEX CB-exhaust	50 × 50 × 50	0.13	0.12
Mixing chamber ATR	Ø = 45; L = 100	0.16	
Mixing chamber SelOx	60 × 30 × 200	0.36	
Mixing chamber burner	Ø = 60; L = 100	0.28	

Table 2
Specifications of tested prototype and developed packaging concept

Specification	Value	Comment
Thermal power	9 kW_{th}	Chemical fuel power
Corresponding APU power	3 kW_{el}	Anode-ratio = 1. 2, η_{FC} = 52%
Efficiency	77%	Based on H_2-production
Efficiency	64%	Based on utilized H_2
H_2-fraction	43%	Dry gas
CO-content	160 ppm	Target: short/medium term: 100 ppm/10,000 ppm
Start-up time	1800 s	Reduction to 600 s possible
Preheating energy	600 kJ	Reduction to 100 kJ possible
Fuel processor volume	13 l/25 l	w/o isolation/with isolation, for packaging concept
Estimated APU volume	44 l	For packaging concept

to direct the synthesis gas flow. However, the major amount of overall packaging volume is wasted on free space within the system, due to a non-optimized arrangement of the components.

On the basis of the principal structure of the experimental prototype as well as on the validated component volumes a much more compact fuel processor is developed. The proposed packaging is based on two ideas. Firstly, to combine the flow directing components with a chemical or thermo dynamical function, and secondly, to use rectangular catalysts, which allow a much denser overall component assembly. The geometry of these catalysts was designed on base of the length and cross-sectional area of the catalysts of the experimental prototype.

Fig. 12 shows a plate like design of a heat exchanger applied between reformer and high temperature shift reactor. The reactors are mounted directly in front of the inlet and outlet cross-sectional areas of the component and no additional bafflers are required to redirect the gas flow. The cross-sectional area of the outlet is increased compared to the inlet, which considers the larger size of the shift reactor. In order to achieve homogeneous flow distribution at the component outlet, each channel of the flow field must have the same pressure drop. This can be realized by widening the longer channels at the outer side of the component compared to the shorter channels on the inner side.

Even though the volume of catalysts, the surface area of heat exchanges, and the volume of mixing chambers was kept constant compared to the experimental prototype, the volume

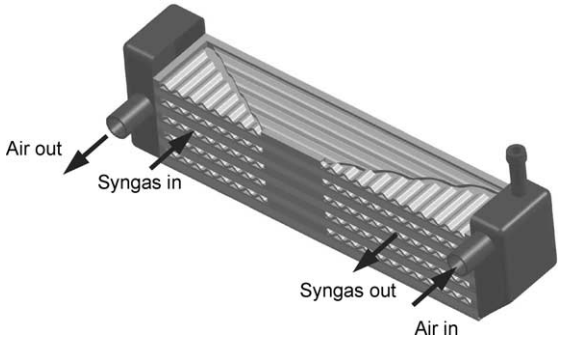

Fig. 12. Heat exchanger concept.

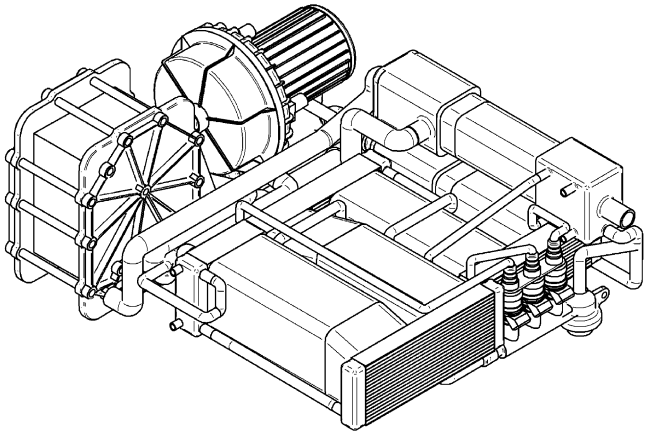

Fig. 13. Packaging of auxiliary power unit.

of the new design is reduced by nearly 70–13 l% (w/o isolation). Fig. 13 shows the integration of the proposed fuel processor together with fuel cell stack and air supply system to a complete auxiliary power unit. The overall volume amounts 44 l.

6. Conclusion

A compact design for a gasoline fuel processor for PEM APU applications was presented. As no detailed validated data for system structure and component geometries are available, an experimental prototype was built and tested. The set-up system proved its general functionality in a power range of 3–9 kW thermal power, corresponding to 1–3 kW electrical power of the auxiliary power unit. Table 2 gives an overview of the collected results.

The volume of the fuel processor experimental prototype was less determined by the size of catalysts and heat exchangers, but much more by housings, tubing and piping as well as a bad arrangement of the components. In the presented fuel processor packaging concept volume was saved by integrating heat exchangers into flow ducts and by using rectangular catalyst bricks. In a design study, this fuel processor packaging was integrated into a complete auxiliary power unit together with a fuel cell stack and air supply system. An overall

system volume of 44 l is reached, which is a reasonable size for a mobile application in a passenger vehicle.

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