Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Power Sources 145 (2005) 639–643
JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

Short communication

On-board fuel cell power supply for sailing yachts

P. Beckhaus*, M. Dokupil, A. Heinzel, S. Souzani, C. Spitta

Zentrum für BrennstoffzellenTechnik GmbH (ZBT GmbH), Carl-Benz-Strasse 201, 47057 Duisburg, Germany

Accepted 22 December 2004
Available online 24 May 2005

Abstract

At the Centre for Fuel Cell Technology (Zentrum für BrennstoffzellenTechnik/ZBT GmbH) in Duisburg/Germany a 300 W fuel cell system of liquid gas-powered operation is currently being developed with focus on leisure boats. An excellent infrastructure in the domain of recreational activities is available for this fuel and users are familiar with the safe handling of liquid gas. On sailing yachts the consumption of electrical power is very restricted during long cruises because of low battery capacities. In this case an additional power supply based on the noiseless fuel cell technology promises an essential comfort increase without disturbing emissions. ZBT's engineers combined their experience in system simulation, reactor design for the gas process and fuel cell technology with the aim of developing a user friendly fuel cell product.

Keywords: PEM fuel cell; Steam reformer; System engineering; APU technology

1. Introduction

Fuel cell systems focussing on electrical power supply applications will have a promising market in the near future. So called auxiliary power units (APU) applicable for a large scale of applications, reaching from power supply for automobiles, leisure range applications to stationary uninterruptible power supply devices (UPS) are in the focus of fuel cell engineering. A main benefit of the APU fuel cell technology is the nearly emission free operation regarding to exhaust gases, noise and vibrations and the high energy efficiency, respectively. A further important aspect is the need of a consumer orientated supply of feed gases. For fuel cells, especially low temperature PEM fuel cells, hydrogen with a high purity is needed. This fuel is barely available today, because of infrastructural aspects and uncertain safety regulations. Furthermore additional fuels are not accepted by the end user if powering an existing energy system with a different fuel. Therefore, the use of gasoline or diesel for automobile applications and natural gas for stationary or household systems is consequentially [1].

The most auspicious field of market introduction for high price components are the leisure range and hobby applications. In these markets the end user is willing to spend more money for modern technologies giving him additional values, higher comfort or an increased fun factor. But still the use of an easily available energy source is favourable. In the field of leisure applications the bottled liquid petroleum gas (LPG) is wide spread. Consumers use LPG mainly in the domain of camping, caravanning, sailing, yachting and other remote applications. This results in an outstanding infrastructure for this fuel worldwide.

ZBT has concentrated its developments in the field of small power supply aggregates running on liquid gas. The system engineering for earlier built units based on hydrogen has now been combined with a new air cooled stack technology and the successful development of small sized steam reforming and gas cleaning reactors for the use of liquid gas. Besides these technological aspects this paper also introduces to further evaluations regarding the product concept of the APU and explains the possible road to a commercial product.

* Corresponding author. Tel.: +49 203 7598 3020; fax: +49 203 7598 2222.
E-mail address: p.beckhaus@zbt-duisburg.de (P. Beckhaus).

0378-7753/$ – see front matter
doi:10.1016/j.jpowsour.2004.12.078

2. Technical product concept

Concerning the development of network-independent power supply aggregates the innovative fuel cell technology proves as a perfectly fitting concept: Fuel cells are notably noiseless, produce only few exhaust gases and avoid disturbing the user by unwanted vibrations. In combination with the use of LPG as feed APUs also allow a rapid market introduction for this technology. Promising markets are applications in the leisure range, for example camping and caravanning or on sailing yachts, where liquid gas is the most spread primary fuel for heating, cooking and cooling. A new technology should use these existing structures to reach the necessary acceptance of the consumer.

At the beginning of the development of the LPG-APU a study on the demands of different applications in the field of leisure range activities was made. This study resulted in the decision to focus the product development on sailing yachts in the beginning. Yachtsmen on the one hand show a high interest in modern technologies and have the economic potential of buying high price components for their boats. On-board load measurements and discussions with professionals and end users lead to the conclusion that a fuel cell APU should be able to deliver between 150 and 500 W electrical power to the dc network on board. Furthermore an additional computer-aided simulation representing the APU behaviour, user demands and different battery technologies demonstrated that a net power output of 300 W is sufficient [2]. The fact that the fuel cell APU is available for noiseless and emission free operation at any time allows the APU a tight operation with the complete energy system on board. This results in the possibility of an independently operating on-board energy management supervising the battery charge, the consumer loads and the fuel cell system. The described simulation [2] also shows that the 300 W APU will need around 500 $g_{LPG}\ kWh_{el}^{-1}$ resulting in approximately one 5 kg bottle LPG for a 14-day cruise for typical consumers.

3. System structure and components

ZBT's auxiliary power unit consists of a multi-stage gas processor to generate a hydrogen rich gas, a fuel cell stack and necessary peripheral components. The main reaction stages shown in Fig. 1 are developed and characterised at the ZBT in parallel. The adaptation of process and control is focused in this work, too. The mobile operation under heavy conditions is considered in the development. The APU will be able to reach a high energy efficiency due to the use of fuel cell anode off gas in the burner of the reformer [3]. The APU is a highly integrated system: a closed water cycle, an optimized heat integration and air cooled system components allow a reduction of necessary installation efforts. Only liquid gas and air have to be supplied, a tube for the exhaust gas stream and the connection to the on-board electrical network have to be installed.

At present the following main components of the APU are developed and characterised at the ZBT in Duisburg:

- *Desulphurisation unit*: An active coal filled cartridge for desulphurisation of liquid gas, which must be exchanged in maintenance cycle of 2 years at frequent use of the APU.
- *Reformer*: Hydrogen production by steam reforming liquid gas under addition of steam and thermal energy (reaction: $C_3H_8 + 3H_2O \rightarrow 3CO + 7H_2$). For heating of the reformer the utilisation of the anode off gas from the fuel cell and additional LPG results in high system efficiency.
- *Shift*: Conversion of carbon monoxide and steam to hydrogen and carbon dioxide to reduce the CO-content to less than 1% (reaction: $CO + H_2O \rightarrow CO_2 + H_2$).
- *CO-purification*: Reduction of carbon monoxide to less than 30 ppm for protection of the fuel cell.
- *Fuel cell*: 450 W power generation with actively air cooled low temperature PEM fuel cell stack powering the balance of plant and the consumer loads.

As ZBT is developer of all these main components of the APU, the system engineering is always in interaction with the component design and test. The possibility to influence the input and output criteria of all subcomponents allows the design of an efficient and flexible APU-system even with the complex architecture shown above.

The status of development of the gas processing unit is shown in Fig. 2. The design of the components has been worked out integral, securing that temperatures and gas concentrations of the reaction stages match well. All reactors have been designed, manufactured and tested in parallel. In September 2004 the gas processor has been coupled for the first time running with artificial anode off gas and propane. The calculated gas concentrations and efficiencies have been

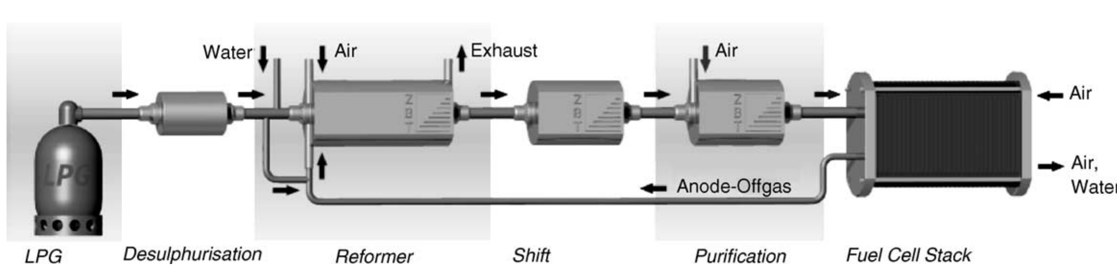

Fig. 1. System structure.

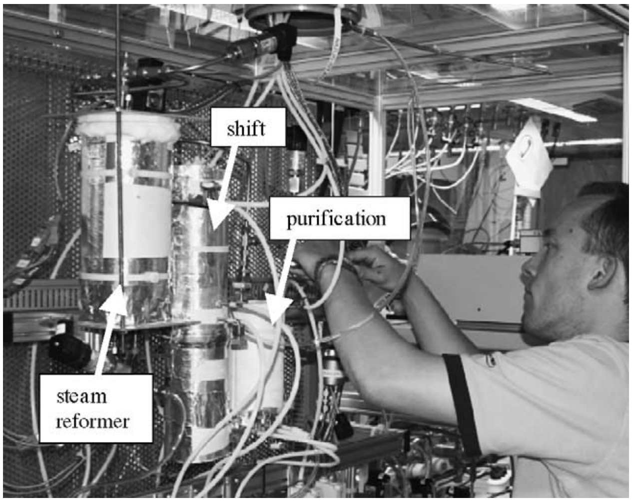

Fig. 2. Steam reformer, shift and CO purification of the 1 kW_{th} gas processing unit in the laboratory test rig.

verified in the testing phase and the system is running satisfactory good. The efficiency of the total gas process at nominal value of 1 kW_{th} hydrogen output has been demonstrated in the laboratory to be ∼65% at the time being. With the use of anode off gas for powering the reformer burner the system reaches an efficiency of ∼87%. A gas concentration of 72% hydrogen with a remaining CO concentration of less than 30 ppm is now available as feed gas for the fuel cell stack.

In parallel to the investigations into the gas process the development of fuel cell stacks at ZBT has been increased. A new concept for actively air cooled stacks with an electrical power of 450 W using reformat gas is now available. A bipolar plate unit composed of two plates can be used for an air or a water cooling system. The currently realized air cooling with integrated transverse channels permits a strong simplification to the heat dissipation of the aggregate. Main part of PEM fuel cell stacks are the bipolar plates. At the moment approx. 30% of the stack costs are incurred by this component. For the economical production of these bipolar plates the injection moulding technology was established at ZBT. In a new high speed injection moulding machine with 300 t closing force bipolar plates can be manufactured from high-conductive compound material. These plates with a thickness between 2 and 4 mm, a size of 600 mm × 1400 mm and with appropriate gas structures are the framework of ZBT's stack technology and will allow reasonable prices for the upcoming fuel cell products (Fig. 3).

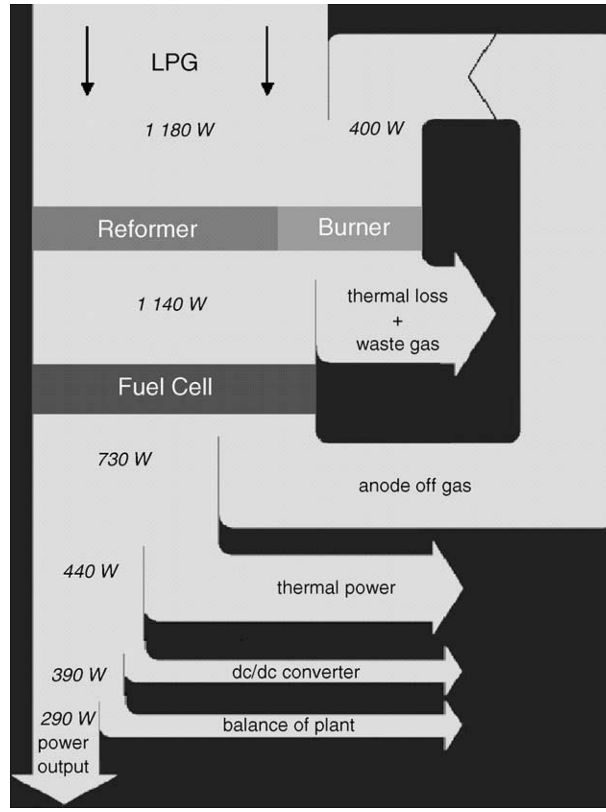

Fig. 4. Sankey diagram of the process based on measured and estimated values.

The physical combination of both technologies is currently worked out in the laboratory test rig. Investigations into necessary peripheral components and their energy consumption are subject of parallel studies as well. The test results from the laboratory together with the computer-aided simulation and further investigations gave input for the Sankey diagram in Fig. 4 visualising the complete system efficiency including peripheral losses. The fuel cell system will have a total efficiency of 25% including the estimated balance of plant and inverter losses while running at nominal load.

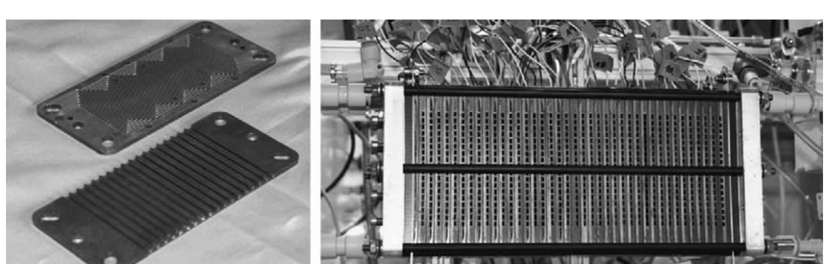

Fig. 3. Injection moulded bipolar plates with machined cooling structure (left) and 40 cell fuel cell stack with a power output >450 W (right).

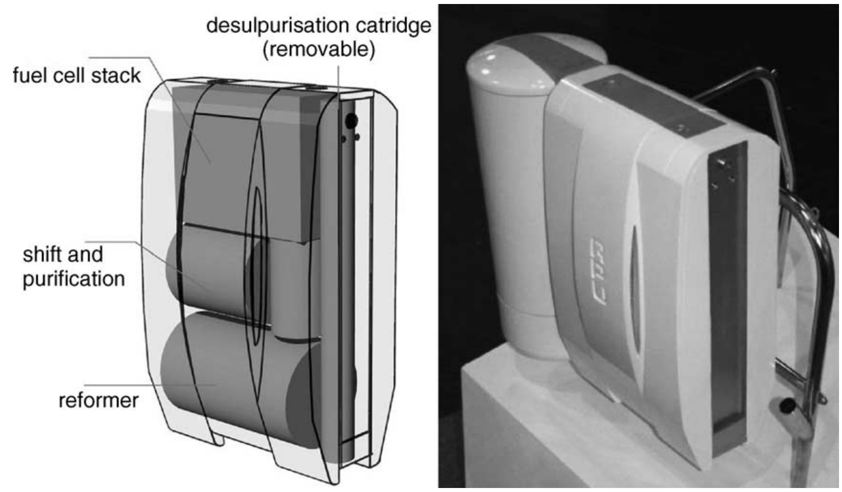

Fig. 5. Component integration (left) and system design model (right).

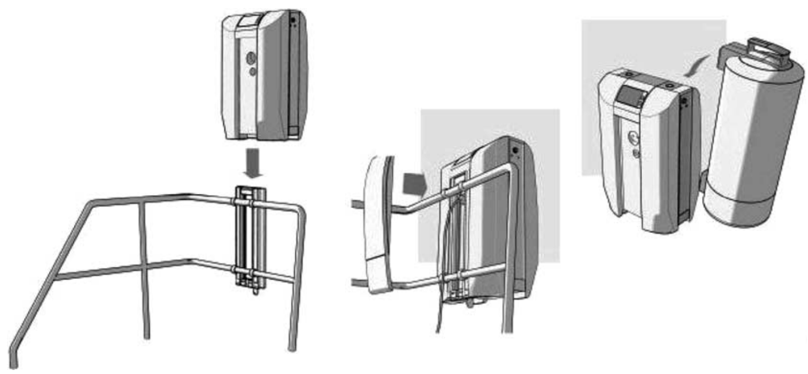

Fig. 6. External mounting of the APU on board a sailing yacht.

4. Flexible installation on-board-bridging for market introduction

In order to be able to use fuel cell systems on board of sailing yachts, they must be adapted to the prevailing conditions. Here the components are exposed to vibrations, large inclination angles and additional to sea air and water. All these aspects have to be taken into account focussing a product on sea. Furthermore the fact that storage room is very limited on sailing yachts gives a limitation to the product design. In a co-operation with the Chair of Industrial Design at the University of Duisburg-Essen the surrounding aspects of the sailing yacht as the area of installation and operation of the APU and function-related product concept aspects of the system have been clarified and different product solutions have been worked out.

Figs. 5 and 6 show the principle design of the preferred product concept and the model that has been presented as product concept on different fairs. The product concept allows a very easy mounting of the system itself to the stern basket. The LPG tank (on the right in Fig. 6) can be attached to the system directly or be stored in the next cockpit storage box as usual. This flexible mounting gives the benefit of quick installing of the APU on different boat types.

The described concept of a significantly easy way of mounting the APU system on sailing yachts allows a high flexibility regarding to market of the new technology. This flexible mounting allows the secure installation of the system on yachts of different shipyards and different sizes as well as the use in other applications. Furthermore this concept allows a smooth market introduction by using existing charter and renting infrastructures. In the beginning it will be beneficial for the manufacturer of the system to get feedback on the system's performance during the cruises and allows a frequent maintenance for the first mini series.

5. Summary and conclusion

Fuel cells have a promising market in the field of power supply aggregates for leisure range applications. Especially sailing yachts offer a high price introduction market with a high demand of power supply units. The ZBT fuel cell technology using LPG as fuel promises to be technically available within the next year. As soon as a powerful technical consortium has been established willingly to develop the available technology to a user friendly and secure product this fuel cell system will have a brisk introduction into the existing leisure range markets. The fuel LPG offers a worldwide supply infrastructure and therefore gives the opportunity of a large market for the APU.

Acknowledgements

Financial support by the European Union and the state of North Rhine Westfalia for the starting of the ZBT GmbH is gratefully acknowledged.

References

[1] J. Mathiak, et al. Problemstellung, Chancen und Risiken von Brennstoffzellen APU's – Fachforum Brennstoffzelle – Entwickler und Anwender berichten, Berlin, 7–8 October 2003.
[2] P. Beckhaus, et al., Power supply for sailing yachts—fuel cell technology with LPG as a user friendly application, in: International Symposium and Workshop Fuel Cells in Aerospace and Maritime Applications, Hamburg, 16–17 September 2004.
[3] H. Brandt, et al., Coupling of a 2.5 kW Steam Reformer with a 1 kWel PEM Fuel Cell—Eighth Grove Fuel Cell Symposium, London, 24–26 September 2003.