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Highly integrated steam reforming fuel processor with condensing burner technology for maximised electrical efficiency of CHP-PEMFC systems

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Abstract

Compact fuel processors using natural gas, LPG and biogas for µCHP fuel cell systems have been developed at ZBT for over 10 years. The technology, based on steam reforming, includes a reformer and a WGS reactor, a water evaporator, heat exchangers and a fuel/anodic offgas burner integrated in an insulated housing. For coupling with a LT-PEMFC today an external preferential oxidation or methanation is added. A HT-PEMFC can be coupled directly to the fuel processor at a temperature level of 160°C. It is discussed that HT-PEMFC systems can exceed the electrical efficiency of LT-PEMFC systems up to five percentage points because of the integration of high quality heat from the fuel cell cooling cycle. In process simulations with AspenPlus® this efficiency advantage could be confirmed. But further investigations concerning heat integration showed for both systems the advantage of using the condensation enthalpy of the flue gas provided by the system burner. This gain in energy offers the opportunity to realise burner operation only with anodic offgas, without additional fuel firing. This study shows the use of condensing burner technology in the fuel processor in comparison of integrating HT-PEMFC heat and/or the use of conventional low-temperature burner technology. For comparison the system boundaries and efficiencies were clearly determined. Heat sources and sinks were identified and quantified along the process chain of steam reforming. A pinch analysis illustrates the requirement of additional heat flows concerning their power and temperature levels.

Keywords: CHP; Fuel processing; HT-PEMFC efficiency; Condensing operation

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1. Introduction

Worldwide, combined heat and power (CHP) fuel cell systems for cogeneration of electricity and heat are seen as an essential component in decentralised power generation. While market introduction of low-temperature (LT-) PEMFC systems for residential applications could be accelerated substantially, high-temperature (HT-) PEMFC and SOFC systems are still in field test status. Currently the main issue for market penetration is increasing operating lifetime, system availability, and reducing factory cost. Furthermore, electrical efficiency also has to be increased in the coming years, especially for PEMFC systems. As one of the main components of a CHP system, an optimised fuel processor can make a big contribution to raise efficiency. Therefore minimal heat losses through the isolation shell and the lowest possible fuel consumption of the burner are required. This primarily includes the implementation of a burner exclusively operating with anodic offgas provided by the fuel cell. Thus, the burner output directly depends on the degree of fuel utilisation in the fuel cell. The less burner power is required, the higher the degree of fuel utilisation can be chosen and the higher the efficiency of the coupled reformer-fuel cell system.

Nomenclature

(μ)CHP system	(micro) combined heat and power system
WGS	water gas shift
LPG	liquefied petroleum gas
LT	low-temperature
PEMFC	polyelectrolyte membrane fuel cell
HT	high-temperature
SOFC	solid oxide fuel cell
P	power (W)
V	volume flow (l/min at STP)
STP	standard temperature and pressure (IUPAC: 0°C, 1 bar)
Q	heat flow (W)
S/C	steam to carbon ratio
η	efficiency
FC	fuel cell
FP	fuel processor
SYS	complete system (fuel processor and fuel cell)
Subscripts	
th	thermal
abs	absolute
el	electrical

2. How to increase efficiency of a steam reforming fuel processor?

Steam reforming fuel processors show potential for increasing efficiency, if it is aimed at realising a high power/heat ratio of the CHP system. This potential is mainly founded in four approaches:

- Optimised system insulation minimises the heat losses through the outer shell, and effective piping and reactor insulation prevent unwanted internal heat flows.
- The energy requirement of a fuel processor system is mostly achieved by burning additional fuel among burning the anodic offgas (AOG) provided by the fuel cell. So there is an opportunity for reducing energy input, if it can be realised to operate the burner only with AOG, without additional fuel firing. This is an important premise for all further investigations in this study.
- Today there is no focus on using flue gas energy by condensing burner technology. Today flue gas energy is mostly used for further heat integration for warm water generation, but this use is not helpful to increase the power/heat ratio.
- If a HT-PEMFC is coupled, there is the possibility to use the HT-PEMFC heat in the fuel processor (e.g. for water evaporating by the heat transfer fluid), which also increases the power/heat ratio.

2.1. Analysing the fuel processor configuration concerning process streams and heat flows

Fig. 1 depicts a flow chart of the ZBT fuel processor, including the assumed temperatures and the required heat transfers. Possible connections of the heat exchangers are part of the simulation results.

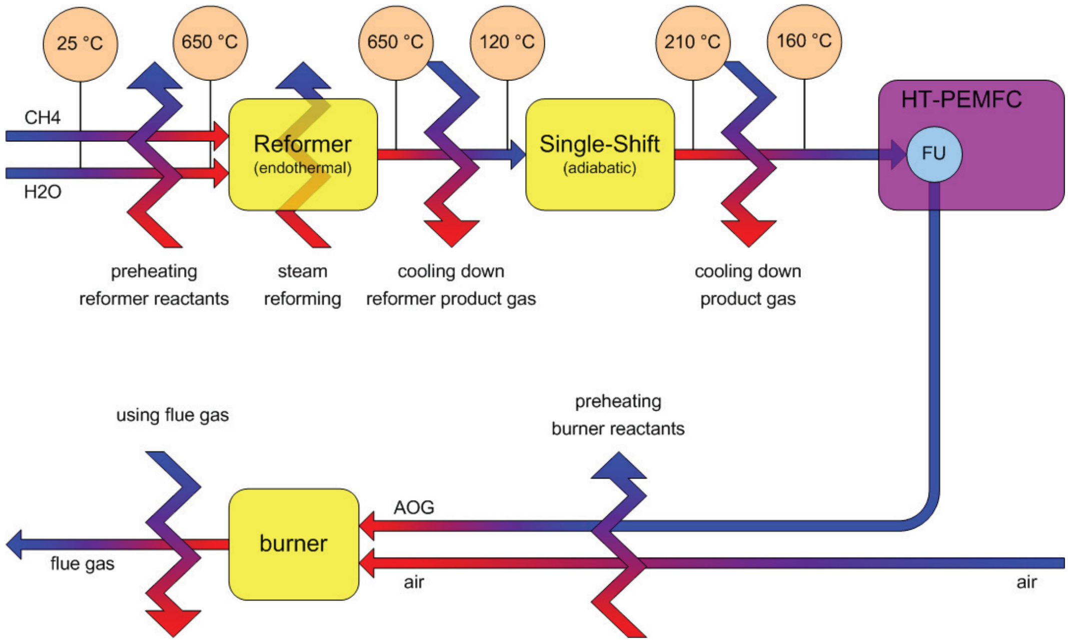

Fig. 1. Flow chart of the ZBT fuel processor for coupling with a HT-PEMFC.

The reformer reactants enter the system at ambient temperature and have to be preheated, evaporated and superheated up to the reforming temperature of 650°C. After the endothermic reforming reaction, the product gas has to be cooled down to the inlet temperature of the adiabatic shift reactor (120°C). The exothermic water gas shift reaction leads to a product gas temperature increase up to 210°C. A subsequent cooling is necessary for meeting the temperature level of the coupled HT-PEMFC (160°C). Depending on the fuel utilization, the system burner is powered only (due to the premise) by the anodic offgas. The flow chart shows a possibility for a recuperative burner heat exchange, which could be important in some cases to guarantee an adequate temperature level in the burner chamber and the reformer reactor, respectively. The fuel processing line starts with the entry of the reformer reactants and ends with the exit of the shift reactor product gas.

In this process chain, internal heat sources and heat sinks exist. To investigate the required value of each heat to be transferred, it is necessary to accomplish a process simulation. This was done using the process simulation software Aspen Plus®. The parameters and boundary conditions were chosen as follows:

- Hydrogen power output fuel processor: $P_{H2} = 4\ kW_{th}$
- Coupling with HT-PEMFC (operation temperature: 160°C)
- Reactants fuel processor:
  - V_{CH4} = 6.12 l/min at STP
  - S/C = 3.0
- Isothermal process control of endothermic reforming reaction at 650°C
- Inlet temperature of the adiabatic shift reactor: 120°C
- Reformate gas outlet temperature of fuel processor: 160°C (due to HT-PEMFC).

The simulation results lead to two internal heat sources and two heat sinks along the processing line:

- Heat sinks:
  - Preheating, evaporating and superheating reformer reactants: 1091 W
  - Reforming reaction: 845 W
- Heat sources:
  - Cooling down reformer product gas: –473 W
  - Cooling down shift product gas: –45 W

The simulation results can be presented in a Q-T diagram, which is shown in Fig. 2. The curve starts on the left with preheating and evaporating the mixture of methane and water. After superheating the reactants, the endothermic reforming reaction follows. After reforming the product gas has to be cooled down for the following exothermic shift reaction. The subsequent cooling of the shift product gas down to PEMFC temperature level is the last step along the processing line. At this point the system's external heat demand is visible: 1428 W.

Beside this heat demand, the Q-T diagram tells us no information about the needed temperature levels. To know at which temperature levels the heat is required, as a next step a pinch analysis is necessary.

In a pinch analysis all cold and warm streams of a connected system are added separately concerning their temperature levels and heat potentials. By sliding the two curves, it is possible to detect what area of the cold streams can be covered by the warm streams. The areas not covered show an external heat demand at a certain temperature level.

The pinch analysis for the fuel processor is shown in Fig. 3. It is clear, that the required heat for the reforming reaction (845 W at 650°C) can only be covered by an external heat source like the system burner. For preheating and evaporating the reformer reactants there is still a heat demand of 574 W at 93°C. Only in the middle area are internal heat exchanges possible, because the warm streams can cover the cold streams (in this optimised illustration, the curves were slid optimally with a pinch point of 0K).

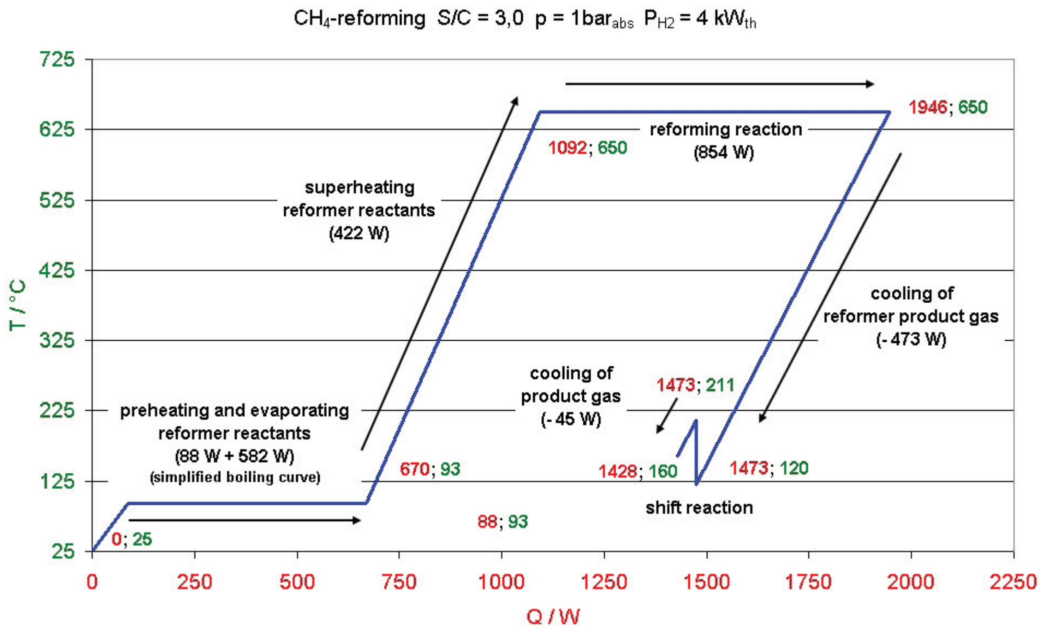

Fig. 2. Q-T diagram.

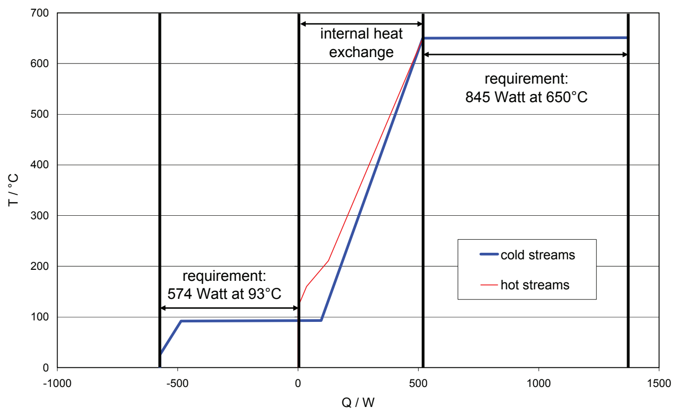

Fig. 3. Pinch analysis.

2.2. Options of heat integration

There are two possibilities to cover the heat demand for preheating and evaporation of the reformer reactants: the energy can be taken out of the flue gas after the heat transfer for the reformer and the recuperator, or the heat of the HT-PEMFC can be used.

Fig. 4 shows possible heat exchanger connections in a CHP system with a coupled HT-PEMFC. The already mentioned opportunity of using HT-PEMFC heat is marked by the light arrow.

In the next step it is interesting to investigate, which of the following variants of heat exchange has which effect on the system efficiencies. Here for the first time in this study the coupling with a LT-PEMFC is also analysed.

- Coupling a HT-PEMFC:
  - Using flue gas energy by **low-temperature burner technology** (flue gas temperature: 76°C, no use of condensing enthalpy in the flue gas)
  - Using flue gas energy by low-temperature burner technology (flue gas temperature: 76°C, no use of condensing enthalpy in the flue gas) <u>and</u> using **HT-PEMFC heat**
  - Using flue gas energy by **condensing burner technology** (flue gas temperature: 40°C).
- Coupling a LT-PEMFC:
  - Using flue gas energy by **low-temperature burner technology** (flue gas temperature: 76°C, no use of condensing enthalpy in the flue gas)
  - Using flue gas energy by **condensing burner technology** (flue gas temperature: 40°C).

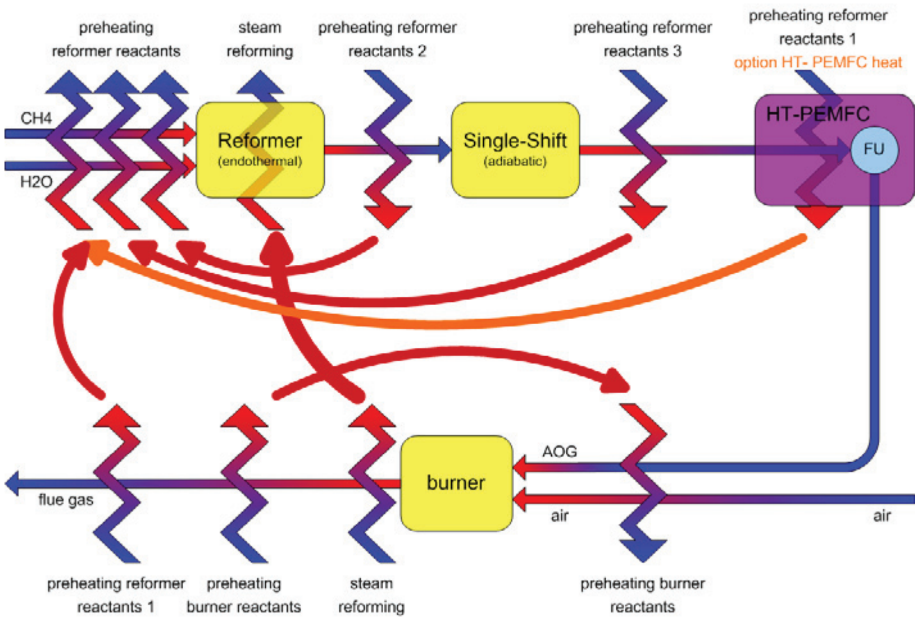

Fig. 4. Options of heat integration using the example of a coupled HT-PEMFC.

2.3. Simulation results

The fuel utilisation (FU) of the fuel cell is an important variable for simulation. Higher FU leads to higher efficiency, but to lower burner power. In the simulation for each case a maximum FU has to be found, which still guarantees enough burner power to operate the fuel processor. Fig. 5 shows the definition of efficiencies.

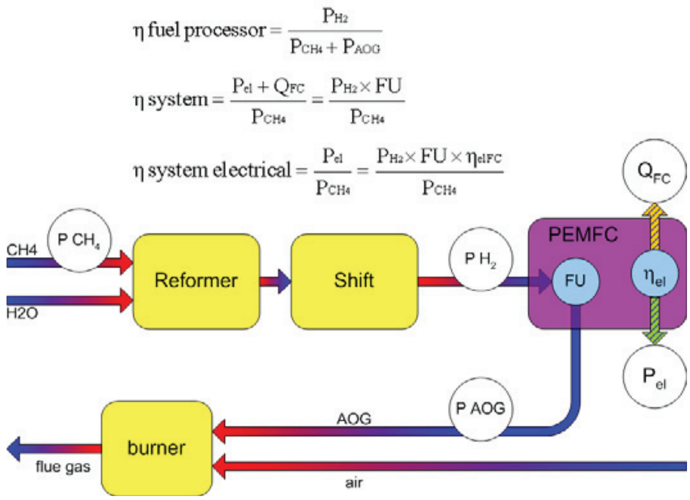

Fig. 5. Definition of efficiencies.

The dependencies of the electrical system efficiency, FU and burner power are shown in Fig. 6 and Fig. 7. Separated in the HT- and LT-PEMFC technology, in both diagrams the conventional low-temperature burner technology is set as a base for comparison with the other variants, the condensing burner technology or (if coupled) the use of HT-PEMFC heat transfer fluid. Each variant is characterised by a maximum FU, which defines the electrical system efficiency (left ordinate) and the required burner power (right ordinate):

- HT-PEMFC: Compared to low-temperature burner technology, using HT-PEMFC heat increases the electrical system efficiency by 5.9 percentage points. The condensing burner technology can almost achieve this increase with **5.5** percentage points.
- LT-PEMFC: An efficiency increase of **3.8** percentage points could be realised by condensing burner operation.

With a focus on the required burner power, the diagrams depict that a power of up to 400 W (coupled HT-PEMFC, Fig. 6) or 300 W (coupled LT-PEMFC, Fig. 7) can be released out of the flue gas by using condensing burner technology.

As an advantage of condensing burner technology there is the option to increase efficiency with both fuel cell types. Furthermore, it can avoid the use of the cooling oil circuit of the HT-PEMFC for heat transfer to the fuel processor.

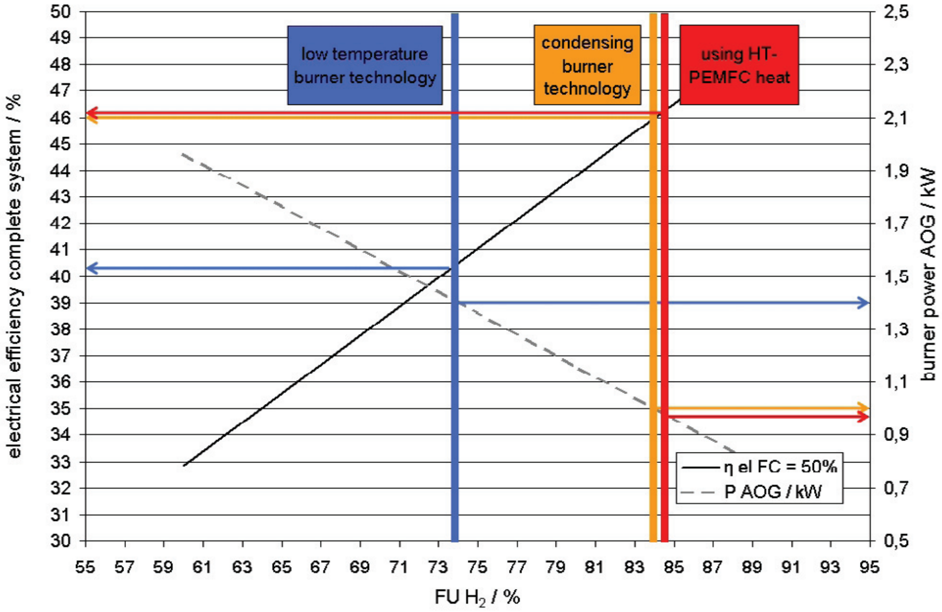

Fig. 6. Dependencies of FU, electric system efficiency, and burner power with a coupled HT-PEMFC.

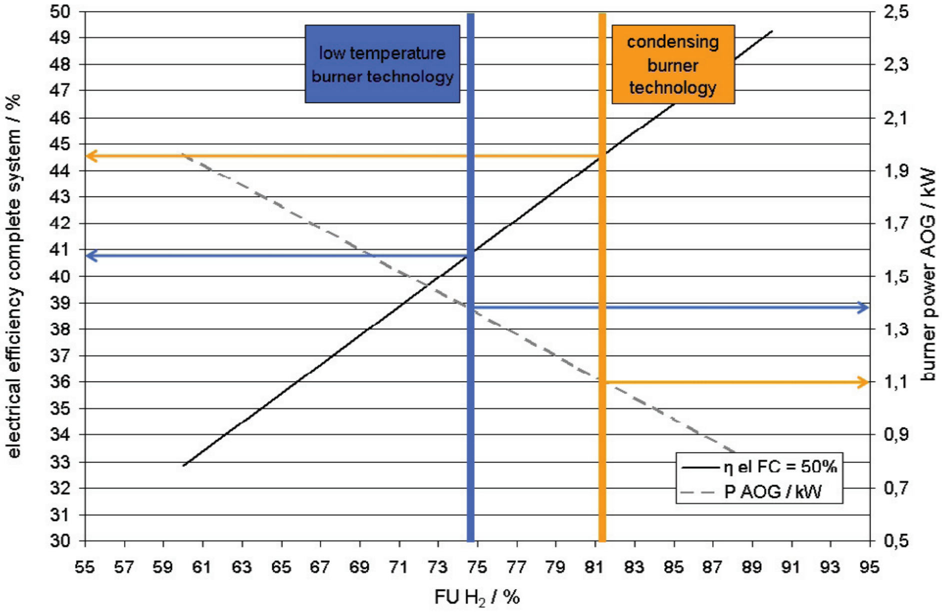

Fig. 7. Dependencies of FU, electric system efficiency, and burner power with a coupled LT-PEMFC.

3. Experimental results

As a first approach, a fuel processor setup was tested with condensing burner technology. Operated with methane a fuel processor efficiency of 82% could be achieved (see Fig. 8). The corresponding flue gas temperature was 54°C. This test showed the feasibility of condensing burner technology.

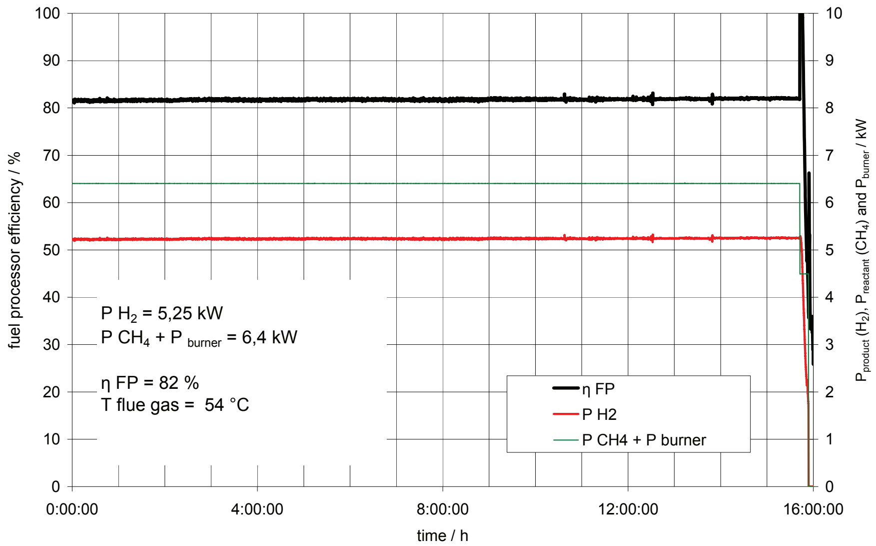

Fig. 8. Measurement results of a fuel processor with condensing burner technology.

4. Conclusions and outlook

This work reports an analysis of possible heat integration of a fuel processor coupled with a HT- or LT-PEMFC. The results show that using HT-PEMFC heat in the fuel processor or realising condensing burner technology can increase the electrical system efficiency by up to 5.9 and 5.5 percentage points, respectively, when compared to conventional (low-temperature) burner technology. The increase due to condensing burner technology is 3.8 percentage points when coupled with a LT-PEMFC.

ZBT decided to realise the condensing burner technology in a real hardware setup, because of the advantage of coupling both types of PEMFC with high efficiency. To get close to the simulated and calculated efficiencies, the key is developing effective heat exchangers. A fuel processor system with an efficiency of 82% has already been built, and was effectively tested with condensing burner technology using methane as fuel. This first hardware setup showed the difficulties of realising an effective flue gas heat exchanger with low pressure drop for process water evaporation. As a next step this hardware setup will be transferred and optimised for a fuel processor for the already mentioned output class of 4 kW_{th}. Measurement results of this system with optimised heat exchangers will be published soon.

Acknowledgment

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