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Selected aspects of the design and operation of the first Polish residential micro–CHP unit based on solid oxide fuel cells

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Abstract

The first Polish micro-combined heat and power unit (micro-CHP) with solid oxide fuel cells (SOFC) was designed and constructed in the facilities of the Institute of Power Engineering in Warsaw. The system was launched in September 2015 and is under investigation. At the current stage the unit is customized to operate on a pre-treated biogas. Adaptation of the fuel processing system, which is based on a steam reformer, makes it possible to utilize other gaseous and liquid fuels, including natural gas. The electric and thermal output of the system, up to 2 kW and about 2 kW, respectively, corresponds to the typical requirements of a detached dwelling or a small commercial site. Functionality of the system was increased by engaging two separate start-up modules, which are used for preheating the system from a cold state to the nominal working conditions. The first module is based on a set of electric heaters, while the second module relies on an additional start-up burner. The startup of the system from ambient conditions up to a thermally self-sufficient stage takes about 7 hours using the electric preheaters mode. Output residual heat was used to heat water to a temperature of about 50°C. The temperature of the flue gases at the inlet to the hot water tank was measured at approximately 300°C. Steam reforming of the biogas was performed by delivering deionized water to the steam reformer in order to maintain the S/C ratio at a range of 2–3.5. Selected aspects of the design and construction as well the first operational experiences are presented and discussed. The numerical modeling methodology is presented as a complimentary tool for system design and optimization.

Keywords: micro-CHP, SOFC, fuel cells, modeling, operation

1. Introduction

Fuel cells are among the breakthrough technologies for clean, efficient and reliable power generation in residential and commercial markets. Solid oxide fuel cells (SOFC) in particular exhibit high electrical and overall efficiency when employed in combined heat and power generators [1]. Over the last two decades numerous alternative designs were under consideration, including micro- and small-scale power systems. Examples include 220 kW hybrids developed at the end of the twentieth century as well the pre-commercial units with power output below 10 kW, including the CERES Power system, the 1 kW Viessman's Galileo, 1.5 kW Blue-Gen by CFCL, and others. Major progress has been made in terms of durability and operational flexibility. Evident cost reduction has been achieved. Several studies discuss in detail the potential for market penetration in different locations in the EU [2–4]. The most widespread application of solid oxide fuel cells is in residential and small commercial micro-combined heat and power (micro-CHP) generation. Such systems offer a great advantage over alternative technologies, including high electrical efficiency, typically over 40%, and overall efficiency exceeding 85–90% [5]. Most existing systems, which were widely discussed during the last few years, represent prototypes offered by several key players. Poland undertook the challenge of developing a competitive solution tailored for the specific needs of Polish customers. Such a system was designed within the framework of the National Strategic Programme—Task 4: Development of integrated technologies of fuel and energy production from biomass, agricultural wastes and other resources. Several consecutive phases of the project were related to the conceptual studies, definition of the system outline, mass and energy balancing of the system in a final configuration, blue printing, design, construction, and finally the operation. As a result a unit with nominal electric power output up to 2 kW and thermal output of about 2 kW was constructed. The system was launched in September 2015 and is currently undergoing experimental investigations under different working conditions.

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2. Modeling platform

Conceptual work related to the definition of the system design was completed using combined mathematical modeling. Several models were developed and implemented as user-defined routines in commercial modeling software Aspen HYSYS 7.5 in order to analyze the behavior of the system in nominal working conditions and in off-design. Detailed models were used to represent the key components of the power unit, including:

- fuel processor,
- high temperature heat exchangers,
- solid oxide fuel cell stacks,
- post-combustor of anodic lean fuel,
- air blower,
- draft fan,
- hot water storage tank.

Table 1: Assumptions, limiting values and tolerances included in the numerical model

Item	Value
steam to carbon ratio	at least 2.2
design point anode inlet temperature	800°C
cathode inlet temperature, °C	650–700
temperature of the exhaust gases leaving the system, °C	130
temperature of the hot water generated by the system, °C	70
temperature of fuel and air supplied to the system, °C	20 and 20
maximum current density of the SOFC stack, A/cm^2	0.25
maximum fuel utilization	0.85
maximum oxidant utilization	0.35
maximum pressure at the anode inlet, bar	1.03
maximum pressure at the cathode inlet, bar	1.03
maximum pressure gradient between the anode and cathode, kPa	3
tolerance of temperature (in heat exchangers, the steam reformer, the SOFC stack,air, water and fuel delivery lines), °C	1
tolerance of the steam-to-carbon ratio	0.01
tolerance of fuel and oxidant utilization factors	0.01
pressure drop in the components, including the heat exchangers, steam, kPa reformer, anodic and cathodic compartments of the SOFC stack, post combustor and the water storage tank	<0.05

The lumped volume modeling (LVM) technique was combined with reduced order models (ROM). The solution algorithm was based on the Gibbs Free Energy Minimization (GFEM) method which is a standard approach, commonly used in power system modeling and optimization [6]. The detailed description of the modeling techniques and theoretical background of the model are discussed elsewhere [7]. The assumptions for the modeling are summarized in Table 1. The modeling platform also included several other routines defining thermal losses, auxiliary power consumption for the control and automation, and the power output correlation accounting for the losses related to DC/AC inverter efficiency. As a result of computer simulations performance maps of the system were generated. The critical part of the numerical investigations was to evaluate the performance of two stacks connected via the fuel line. For that purpose the performance of the stand-alone stacks, considered as an SOFC module, was analyzed and can be seen in Fig. 1.

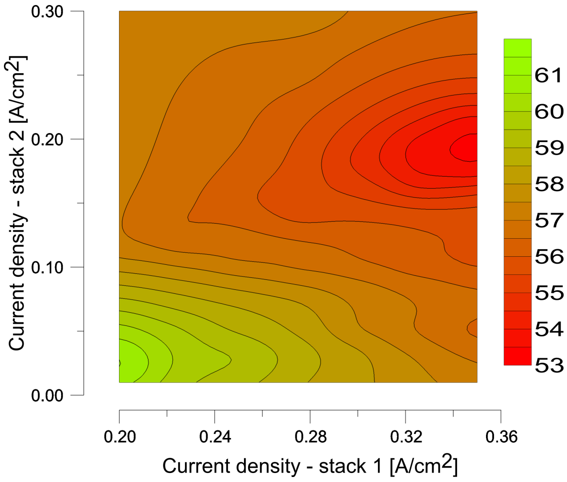


Figure 1: Performance map of the two identical stacks connected via the fuel line

As can be seen in Fig. 1 the effects of varying the current density in each of the 1,300 W stacks affect the overall electrical efficiency of the SOFC module. The second stack by definition operates on a lean fuel, therefore low current density should be expected. The high current density in the first stack is accompanied by a high value of the fuel utilization factor. This leads to the reduction of the lower heating value of fuel incoming to the second stack. For that reason, the SOFC module can achieve high efficiency only when the first stack remains at a low current density, not exceeding the range of 0.22–0.24 A/cm^2.

3. Design of a micro-CHP system

Determining the final configuration of a power system is a complex process which has to factor in legal, administrative, technical and operational limitations. Firstly, the unit has to comply with national and European regulations on emission and efficiency standards. Secondly, it has to comply with safety standards and codes. Safe and intuitive operation is assured by the customized automation and control system. Moreover, in the initial phase the prototype needs to be equipped with a large number of sensors, such as thermocouples, pressure transducers, and a mass-flow controller in order to allow thorough experimental evaluations. Precisely because the discussed unit was designed as a first-of-a-kind, a high level of redundancy of instrumentation was foreseen. This was required to enable precise analysis of the working conditions of the entire system and its sub-modules during different working conditions. Initial work was related to defining potential configurations which can be realized using the existing equipment. At this stage the availability of key components such as heat exchangers, fuel processors, post-combustor and SOFC stacks was taken into account. Since fuel in the form of a pre-treated biogas was considered, three fuel processing techniques were analyzed. Autothermal steam reforming (ATR), allothermal steam reforming (SR) and partial catalytic oxidation (CPOX) were analyzed. A detailed study on the raw fuel conversion discusses advantages and disadvantages of alternative solutions [8]. Steam for the purpose of reforming the feed can be delivered either through the continuous supply of deionized and demineralized water or through recirculation of anodic off-gas. The first option is not viable in residential applications on the grounds of efficiency and economy due to the increase in complexity of the system and additional auxiliary power consumption. The second option offers several advantages including: high achievable overall fuel utilization which leads to a high electrical efficiency of the system; operational flexibility when a machine is engaged in the recirculation of part of the anodic off–gas; the ease of adapting the working conditions of the fuel cell stack to meet the requirements of the steam reforming process, including a proper steam to carbon ratio (S/C) [8].

The conceptual design was followed by blueprinting and the construction phase. Several operational criteria were under consideration:

1. The possibility to maintain a relevant temperature of the incoming fuel and oxidant streams to the SOFC stacks.
2. Proper parameters in the post-combustor of anodic lean fuel.
3. Ability to complete the start-up procedure using either the electric heaters or the start-up burner.
4. Thermal self-sustaining design enabling a high level of thermal integration.
5. Stabilization of key operational parameters during steady-state operation.
6. The possibility to use a start-up fuel mixture (hydrogen and nitrogen) before the steam reformer is preheated to its operating temperature.
7. Fuel flexibility which makes it possible to modify the composition of the incoming fuel.

As a result, a micro-combined heat and power unit with a nominal power output of 2 kW_{el} and about 2 kW_{th} was constructed and operated. The unit is shown in Figs 2 and 3. The system is based on two identical SOFC stacks connected serially through the fuel line. Each of the fuel cell stacks is enclosed in high temperature insulation.

The other components of the system, which operate at an elevated temperature, such as the heat exchanger, the fuel processor, and the post-combustor, were located in a high temperature chamber. A high level of thermal integration and the use of high quality insulation delivered a reduction in thermal losses and resulted in the gas leaving the hot zone at a temperature below 300°C. The low temperature heat is withdrawn from the exhaust stream, which leaves the high temperature chamber in the form of hot utility water. It can be either directly consumed or stored in a 140 liter tank. Such a solution enables easy adaptation to residential applications with a demand for electricity and hot water, both subject to hourly and daily variations. The basic characteristics of the system are summarized in Table 2. The functionality of the system was increased by engaging two separate start-up modules which are used to preheat the system from a cold state to nominal working conditions. The first module is based on a set of electric heaters, which gradually increase the temperature of the key components by directing hot gases via internal piping. The second module relies on an additional start-up burner, which is embedded in the high temperature chamber. As mentioned earlier, the novelty of the system was the serial connection of two identical SOFC stacks via the fuel (anodic) line. Each of the two 1,300 W stacks is based on 60 square cells of 128 cm^2 each. The electrolyte supported cells (ESC) used in the stacks operate at an elevated temperature, exceeding 800°C. Control algorithms play a key role in the operation of advanced power systems, including generators with solid

Figure 2: Micro-combined heat and power unit with solid oxide fuel cell stacks—view showing the 140 l hot water storage tank

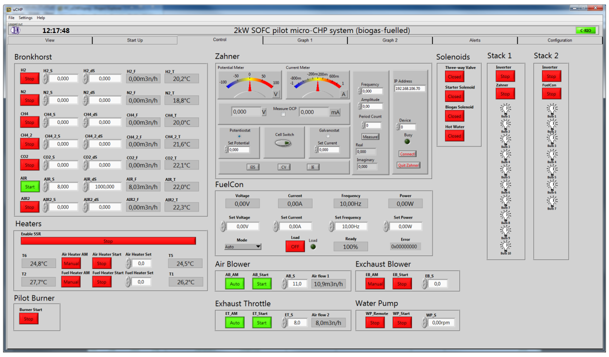
Figure 3: Micro-combined heat and power unit with solid oxide fuel cell stacks—view showing the high temperature chamber

Table 2: Assumptions, limiting values and tolerances included in the numerical model

Item	Value
Nominal electric power, kW	2.0
Thermal power, kW	Up to 2.0
Electric efficiency, %	within the range of 32–44
Overall efficiency, %	>80
Dimensions (H x L x D), mm	1,880×1,370×1480
Weight, kg	≈700
Fuel type	Biogas (cleaned), hydrogen/nitrogen mixture
Hot water storage tank capacity, l	140
Water temperature, °C	30–70
Power supply during start-up (electric heaters), V	1×400
Power supply during start-up (electric heaters), A	18.5
Type of thermal insulation	Micro-porous, mineral wool
Gas connections, mm	hydrogen: 6 nitrogen: 6 methane: 6 carbon dioxide: 6 air: 12
Water connection, inch	¾
Sensors	49 N-type thermocouples 13 precise pressure transducers Set of mass-flow controllers

oxide fuel cells [9, 10]. For that reason a universal control system was developed and implemented in the installation. Safe control and monitoring of the processes were achieved using National Instruments LabVIEW software and a cRIO controller. The following objectives were considered during formulation of the functionality:

- safe operation of the system, including the emergency procedures,
- redundancy of control, separation of the control and emergency functions from the user interface,
- flexibility: the ability to reconfigure as many parameters of the system as possible through software settings,
- stable and repeatable measurements,
- robustness and resistance to harsh conditions (electromagnetic noise, elevated temperature and others),
- open architecture enabling easy modification of the system.



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2kW SOFC pilot micro-CHP system (biogas-fuelled)

Bronkhorst

	S	dS	F	T
H2 Stop	H2_S 0,000	H2_dS 0,000	H2_F 0,00m3n/h	H2_T 20,2°C
N2 Stop	N2_S 0,000	N2_dS 0,000	N2_F 0,00m3n/h	N2_T 18,8°C
CH4 Stop	CH4_S 0,000	CH4_dS 0,000	CH4_F 0,00m3n/h	CH4_T 20,0°C
CH4_2 Stop	CH4_2_S 0,000	CH4_2_dS 0,000	CH4_2_F 0,00m3n/h	CH4_2_T 21,6°C
CO2 Stop	CO2_S 0,000	CO2_dS 0,000	CO2_F 0,00m3n/h	CO2_T 22,1°C
AIR Start	AIR_S 8,000	AIR_dS 1000,000	AIR_F 8,03m3n/h	AIR_T 22,0°C
AIR2 Stop	AIR2_S 0,000	AIR2_dS 0,000	AIR2_F 0,00m3n/h	AIR2_T 22,3°C

Heaters

Enable SSR Stop

T6	Air Heater AM	Air Heater Start	Air Heater Set	T5
24,8°C	Manual	Stop	0,0	24,5°C
T2	**Fuel Heater AM**	**Fuel Heater Start**	**Fuel Heater Set**	**T1**
27,7°C	Manual	Stop	0,0	26,2°C

Pilot Burner

Burner Start Stop

Zahner

Potential Meter

Current Meter

0,000 V

Measure OCP ☐

0,000 mA

Potentiostat ○

Set Potential 0,000

Cell Switch

Galvanostat ○

Set Current 0,000

Frequency 0,000

Amplitude 0,00

Period Count 0

Real 0,000

Imaginary 0,000

IP Address 192.168.106.70

Device 0

Busy

FuelCon

Voltage	Current	Frequency	Power
0,00V	0,00A	10,00Hz	0,00W
Set Voltage	**Set Current**	**Set Frequency**	**Set Power**
0,00V	0,00A	10,00Hz	0,00W

Mode Auto

Load OFF

Load

Ready 100%

Error 0x00000000

Air Blower

AB_AM Auto

AB_Start Start

AB_S 11,0

Air flow 1 10,9m3n/h

Exhaust Blower

EB_AM Manual

EB_Start Stop

EB_S 0,0

Exhaust Throttle

ET_AM Auto

ET_Start Start

ET_S 8,0

Air flow 2 8,0m3n/h

Water Pump

WP_Remote Stop

WP_Start Stop

WP_S 0,00rpm

Solenoids

Three-way Valve Closed

Starter Solenoid Closed

Biogas Solenoid Closed

Hot Water Closed

Stack 1

Inverter Stop

Zahner Stop

Stack 2

Inverter Stop

FuelCon Stop

Figure 4: The control panel of the micro-CHP system with solid oxide fuel cells

The control panel of the system can be seen in Fig. 4. It includes adjustable and monitored parameters for both stacks included in the system. The importance of the selected parameters for the performance of two stacks connected serially was previously discussed [11].

Detailed specification of the system can be found in [12].

4. Operation of the unit

The configuration of the system is adapted for two alternative start-up procedures. The first one uses two electric heaters (air and start-up fuel) and the second one takes advantage of the installed start-up burner. Thanks to the second start-up procedure, the system can be operated in island mode supported by an appropriate DC/AC converter coupled with a car battery or a small portable power generator. Within the start-up phase presented in Fig. 5, six stages can be distinguished:

1. stabilization of the SOFC stacks operating temperature (800–860°C),
2. ignition of the afterburner,
3. deactivation of the air and fuel heaters—enabling heat exchangers to preheat air,

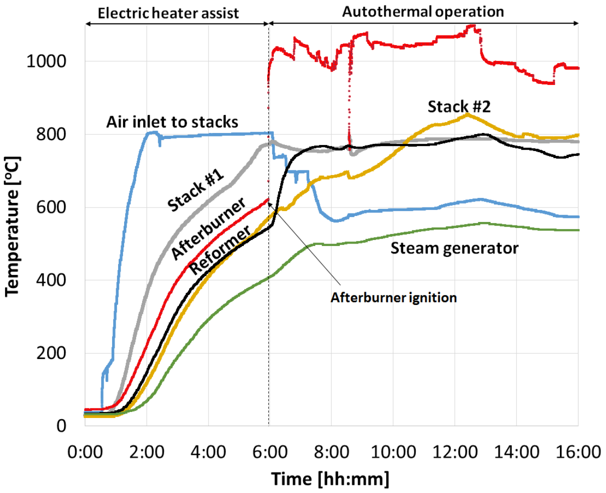

Figure 5: System component temperatures during start-up

4. stabilization of the steam generator temperature and the beginning of steam production for the stream reforming reaction,
5. stabilization of the operating temperature of the steam reformer, followed by a gradual switch from H_2/N_2 start-up fuel to the pre-treated biogas,
6. stabilization of key operating parameters of the system.

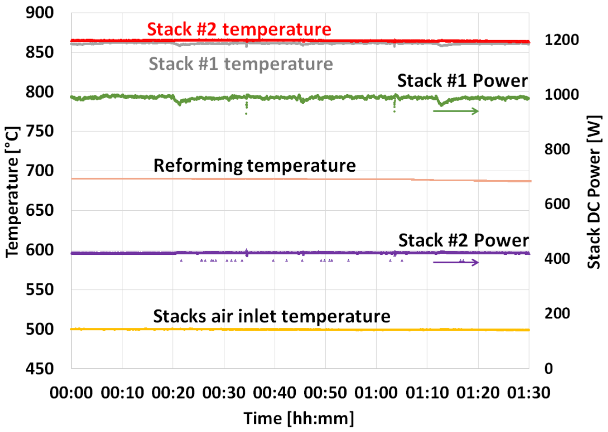

Figure 6: Selected parameters of the system during thermally-self sustainable operation

During the start–up phase, the SOFC stacks are fuelled with a hydrogen and nitrogen mixture. When afterburner ignition occurs, the exhaust gas temperature reaches 1,000°C. The exhaust stream is used to maintain the reformer temperature and preheat the air in the heat exchanger. The reformer temperature gradually stabilizes at ca. 650–750°C. At this temperature the electric air and fuel pre-heaters are turned off and the system is switched to biogas. The inlet fuel undergoes a steam reforming reaction and converts to a reformate composed of (dry basis) 56.0%, 12.5%, 23.0% and 8.4% of hydrogen, carbon monoxide, carbon dioxide and methane, respectively. The system operates with a steam-to-carbon ratio of 2.0 to 3.5. During stable operation (Fig. 6) exhaust gases are further used to heat up water in the domestic hot water tank. The temperature in the high temperature chamber oscillates around 450°C. The system DC power peaks at 1,800 W_{el}. The average temperature of both stacks is controlled in a range from 850 to 860°C by modulating the air flow. The voltage of the SOFC stack channels (10 cells each) must be maintained above the value of 6 V. The DC electric efficiency of the system is 32% (LHV-based). The DC/AC inverters were integrated in the system to convert the DC output of the stacks to 230 V AC. Additionally, the inverters synchronize the micro-CHP unit with the power grid.

5. Conclusion

The conceptual design of the system was developed after 5½ years of research activities. In the next phase the system was constructed and operated. Operational experience to date indicates that the system achieved the expected electrical efficiency of above 30%. The maximum electrical output power from both SOFC stacks was 1.8 kW_e at stable conditions. After thermal stabilization of the steam reformer, conversion of synthetic biogas was started at a temperature of 700°C. For these reforming conditions methane was converted from 60% vol. at the inlet to the reformer to about 8% vol. at the reformate outlet with an assumption of dry fuel mixture. Further optimization of the micro—CHP unit could achieve higher reforming temperature and a much better methane conversion process together with an improvement in the overall efficiency of the whole system. It has to be noted that the current version of the micro-combined heat and power unit is a first-of-a-kind prototype which has not yet been optimized. Serving as an experimental platform for further investigation of power generation in micro-combined heat and power systems with SOFCs, the system exhibits a high level of redundancy of instrumentation and sensors. Additionally, the design of the high temperature chamber was oriented towards easy access to each of the components enclosed in the hot zone. The existing fuel processing unit based on steam reforming can be adopted for operation with alternative fuels. At the current stage of operation of the system, the performance on simulated biogas and hydrogen/nitrogen mixtures was analyzed.

Acknowledgments

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