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Development of a Fuel Flexible, Air-regulated, Modular, and Electrically Integrated SOFC-System (FlameSOFC)

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Abstract

The present paper summarizes experimental results from the operation of the SOFC based micro-CHP unit developed within the framework of the project FlameSOFC. The project is co-financed by the European Commission as an Integrated Project within the 6th framework program. The objective is the development of an innovative SOFC-based micro-CHP system capable of operating with different gaseous and liquid fuels and fulfilling the technological and market requirements at a European level. The partners involved in the FlameSOFC project bring together a sufficient number of important European actors on the scientific, research and industry level including SMEs and industrial partners from the heating sector. The presented work concerns the operation of the 2nd phase prototype FlameSOFC system, with a 1 $kW_{el.}$ SOFC stack and natural gas as feedstock.

1 Introduction

The objective of the integrated European project FlameSOFC is the development of a multi-fuel, modular SOFC micro-combined heat and power (CHP) system, which is capable to operate with gaseous and liquid hydrocarbon fuels, fulfilling the relevant technological and market requirements at a European level. The main focus concerning the multi-fuel flexibility lies on different natural gas qualities and LPG but also on liquid fuels (diesel like heating oil). The target nominal net electrical output is 2 $kW_{el.}$, which is expected to represent the future mainstream high volume mass market for micro-CHPs. The advanced planar SOFC stack [1], that constitutes the core part of the unit, enables fuel flexibility as well as a simple and compact system design. The SOFC stack is combined with a novel, compact and robust fuel processor [2-7], which is able to process many different fuels without catalytic components. Apart from the fuel processor, the periphery of the developed system incorporates a multi-purpose off-gas burner [8-13], compact heat exchangers [14], a vaporizer [15] and a soot trap. The integration concept of the components leads to a very simple and reliable system design. The efficiency targets are > 30 % net electrical efficiency and > 90 % total CHP efficiency. The final application is going to be a micro CHP system for single or two-family residential homes with electrical grid connection.

2 Technological Solution

An overview of the technological solutions provided in FlameSOFC and the 3-D drawing of the complete 2nd prototype system is given in Figure 1. The proposed system can generate electrical power from gaseous fuels like natural gas or LPG as well as from liquid fuels like heating oil. The overall system is split up into three main sections: the fuel processing stage, the SOFC stack with power electronics and the BoP section. The entrance section of the fuel processor shows two separate routes for the pre-treatment of gaseous and liquid fuels, respectively.

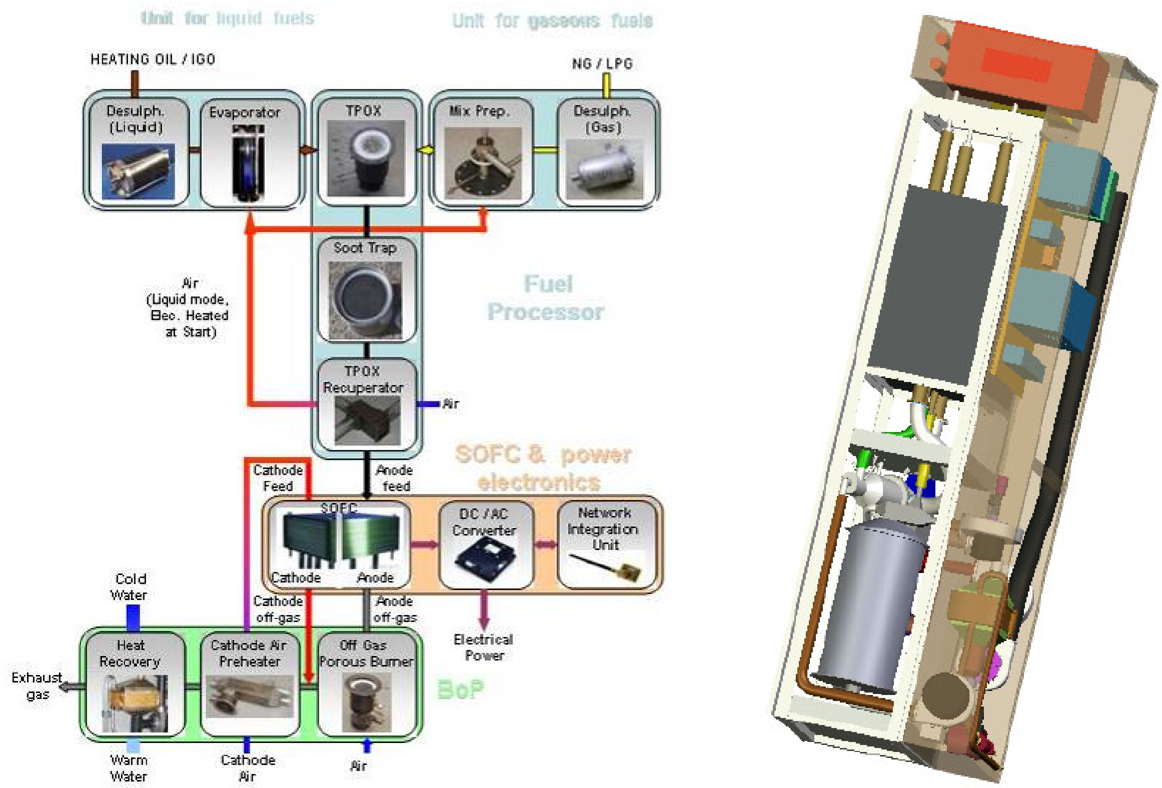

Figure 1: Schematic diagram of the FlameSOFC micro CHP system and 3-D CAD drawing of 2nd Phase Prototype.

In both cases the fuels are desulphurised after entering into the system [15]. As the fuel has to be in gaseous phase when entering the reformer, liquid fuels are vaporized in a tailored designed vaporizer [16]. In the TPOX reformer the gaseous fuel flow, mixed with an under-stoichiometric amount of air (λ in the range of 0.42 - 0.45) performs a partial oxidation reaction at temperatures in the range of 1200 °C - 1400 °C. The reformer is based on the porous burner technology, which shows an enhanced heat and mass transport within the reaction zone as well as high heat recuperation against the flow direction. Both effects help to extend the operational range towards low air ratios, which is normally limited by blow off and / or soot production. Low air ratios are essential for the achievement of high hydrogen and CO yields, which comprise the useable fuel components of synthesis gas for utilization in solid oxide fuel cells. In order to obtain sufficient reaction speeds in the TPOX reformer the temperatures in the reaction zone must be high and preferably in the mentioned range of 1200 °C - 1400 °C. The targeted temperature range at low air ratios is only achievable by additional preheating of the educts. Furthermore, before the fuel reformate can be sent to the SOFC stack, it has to be cooled down to temperatures lower than 850 °C in order to prevent overheating and damaging of the SOFC stack. For this reason a heat exchanger (TPOX recuperator) is installed after the soot trap. It preheats the fresh air inlet of the TPOX reformer and cools the fuel reformate down to SOFC operating temperatures. By preheating the air supply of the fuel processor the TPOX reformer can reach the required high operating temperatures at low excess air ratios λ. The preheated air either enters at the evaporator enabling an efficient vaporization and mixing of liquid fuels, or is mixed with the gaseous fuel in the specially designed mixing chamber. After the TPOX reformer a ceramic soot trap is implemented for removing any possible soot traces formed in the reformer [17], which could poison the SOFC anode. The regeneration of the soot trap is a main challenge since anode supported cells do not endure oxygen at elevated temperatures as it would occur in the case of conventional regeneration procedures based on the injection of air. The purified and temperature conditioned reformate fuel (synthesis gas) enters the SOFC stack at the anode inlet. In the stack the H_2 and CO components are reacting with the oxygen transported through the electrolyte from the cathode side and electrical current is generated. Regarding the interconnection to the electrical power network the current is converted with power electronics, showing an overall efficiency (DC/DC converter plus DC/AC inverter) of more than 90 %. The communication of the FlameSOFC unit with possibilities for energy management options is performed in the network integration unit. The hot anode off-gas containing small amounts of unconverted H_2 and CO (during normal operation) is post-combusted in the off-gas burner based on the porous burner technology. The hot cathode off-gas, which consists of oxygen depleted air, is mixed with the off-gas burner exhaust and a large portion of the overall heat content is recuperated in the cathode air preheater by heating up the cathode air supply. The final exhaust gas stream after the cathode air preheater flows to a heat recovery unit (which depending on the heat requirements may be fed also by an auxiliary burner), where hot water for heating purposes is generated.

Two FlameSOFC micro-CHP units, developed at two different stages, were constructed and were tested under laboratory conditions, in order to prepare and assure the functionality of the final prototypes at the demonstration sites. During the first two project years, prototypes of all components were developed, tested and evaluated concerning their functionality for the FlameSOFC unit.

Based on the results and experience of the 1st phase prototype the 2nd phase prototype was designed and manufactured [18-21]. Therefore a highly integrated design has been implemented and the system is based on three main sections (stack, hot BoP and reformer components, cold BoP and electronic devices), see Figure 2.

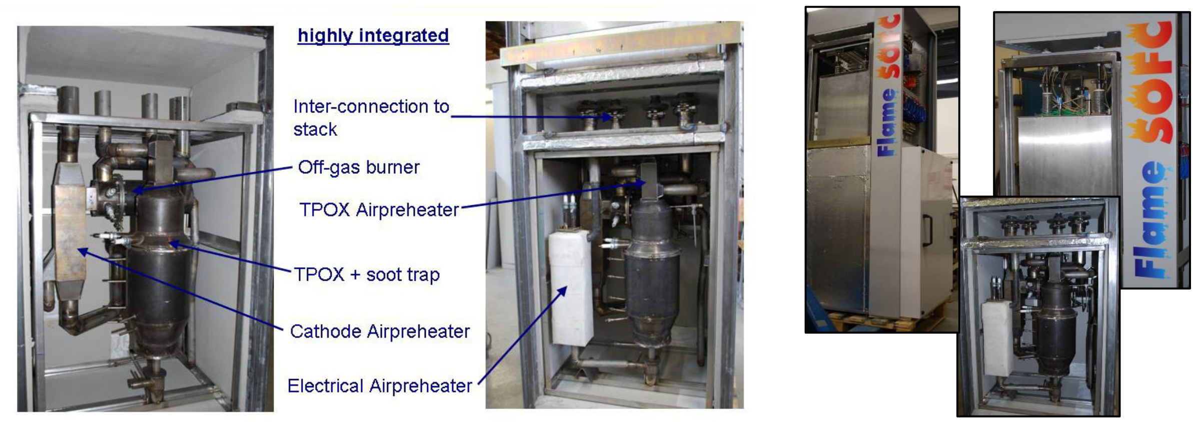

Figure 2: 2nd Phase Prototype of the FlameSOFC micro-CHP system.

3 Experimental Conditions and Results of the 2nd Phase Prototype

The operation of an SOFC micro CHP-system is mainly based on the boundary condition of the stack. Therefore, the boundary conditions for stack operation are summarized in Table 1.

Table 1: Summary of stack requirements.

Parameter	Limit/ target
Thermal gradient stack core material	50 K/min
Temperature difference anode/ cathode/ stack core	100 K
Maximal temperature for oxidizing atmosphere	400 °C
Minimal temperature to draw electric current	700 °C
Pressure difference anode / cathode	≤ 30 mbar

Table 2: Flow rates of gas, air branches according to mass and heat balance simulations for normal operation (natural gas case, u_f = 65 %, λ_{TPOX} = 0.42)

Load	25 %	50 %	100 %
Flow rate natural gas	2.8 l_N/min	5.9 l_N/min	13.3 l_N/min
Flow rate afterburner air	7 l_N/min	10 l_N/min	53 l_N/min
Flow rate cathode air	162 l_N/min	297 l_N/min	631 l_N/min
Flow rate TPOX air	11 l_N/min	14 l_N/min	44 l_N/min
Fuel power related to the lower heating value	1.7 kW	3.5 kW	8 kW

The thermal gradients together with the allowed temperature differences between the cells and interconnectors form the main obstacles for a fast heat-up rate of the stack. However, it should be noted that these values have mainly the sense of being “on the safe side” of stack operation, since statistically credible data is not available due to high costs. Table 2 shows a summary of the flow rate for the different streams that are based on simulation results for the natural gas case for representative operational parameters, a fuel utilization of 65 % in the stack and a TPOX air ratio of 0.42. For start-up and load rejection operation the afterburner had to handle the reformate gas from the reformer without electrical conversion in the stack. This affected of course the amount and composition of the anode off-gas and consequently the heat and mass balance of the system. The operational results of the 2nd phase prototype are presented in Figure 3. It can be seen, that after ≈ 16 hours of preheating the system in start-up mode (the first 20 min. in this mode an electrical preheating is needed) a stable operation can be achieved. The current collection was performed with an electronic load in contrast of the inverter of the final system. The results of the operation is summarized and presented in Table 3.

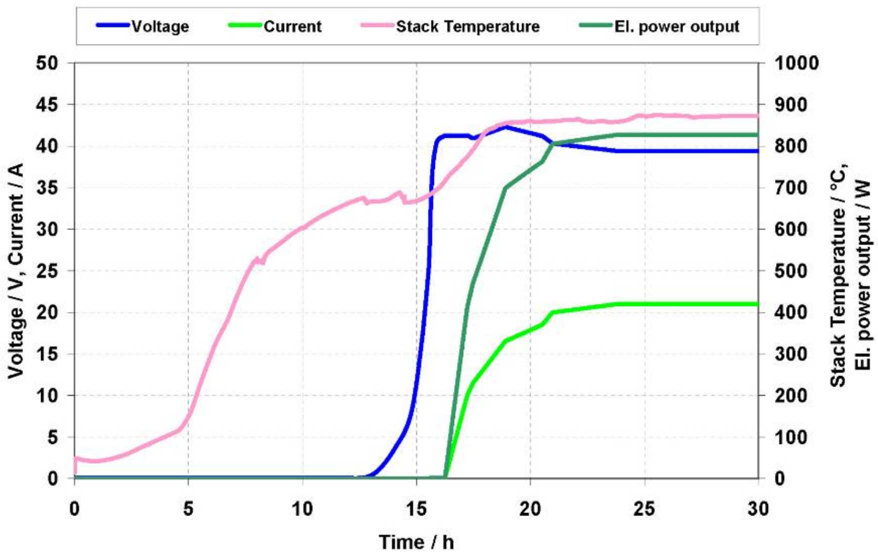

Figure 3: Operational results of the 2nd Phase Prototype FlameSOFC with 1 kW$_{el.}$ SOFC stack.

Table 3: Overview of the operational results of the 2nd Phase Prototype FlameSOFC (1 kW$_{el.}$ stack).

Temperature anode in	676°C	Cathode inlet pressure	28 mbar
Temperature anode out	798°C	Stack core temperature	858°C
Anode inlet pressure	24 mbar	Voltage	39,4 V
Temperature cathode in	748°C	Current	21,0 A
Temperature cathode out	823°C	Power output	827 W

4 Summary

The 2nd Phase Prototype of the FlameSOFC micro-CHP unit has been operated successfully with a 1 $kW_{el.}$ stack. All main components like TPOX reactor, heat exchangers and afterburner operated successfully in combination and fulfilled their specifications. It has been shown that the system achieved 830 $W_{el.}$ and operated stable.

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