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Analysis of a micro-CHP unit with in-series SOFC stacks fed by biogas

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Abstract

This paper presents results of a recent evaluation of a conceptual micro-CHP units in two alternative configurations. Parallel and in-series connections of two identical commercial electrolyte-supported SOFC stacks were under evaluation. In order to achieve high overall fuel utilization in the system enabling high electrical efficiency, both concepts were analyzed with respect to operational regimes typical for SOFC stacks. Numerical analysis included several possible configurations of complete a system with fuel processor, SOFC stacks and BoP components. Evaluation of the in-series connection was performed using experimental setup with a commercial SOFC stack to reproduce operating conditions obtained from the model. Validation of the concept was necessary to qualitatively and quantitatively determine possibility of operating second stack on lean fuel originating from the anodic compartments of the first stack. Results of the comparative analysis presented in this paper were used to aid in defining optimal outline of a micro-CHP power system. Predictions of the models were in agreement with preliminary experiments, proving the concept of in-series stacks configuration viable. Electrical efficiency increases for the system with two in-series stacks, and value of 46%$_{LHV}$ can be achieved in the micro-CHP system with SOFC.

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Keywords: micro-CHP, SOFC, modeling, experimental validation

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1. Introduction

Several alternative designs of efficient power generator with fuel cell were previously studied. At the power range up to 5 kW the only justified configuration of a system with solid oxide fuel cells is either combined heat and power generation, or alternatively poly-generation with additional cooling capabilities or alternative solutions such as simultaneous hot utility water preparation and space heating. To benefit from the high electrical efficiency of direct electrochemical oxidation of a fuel in fuel cells, optimal

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designs of micro-power units are sought.

Typical solid oxide fuel cell stack, despite being highly efficient does not completely utilize fuel. For that reason different solutions are considered to achieve high overall fuel utilization, including recirculation of depleted anodic fuel with blowers or ejectors [1]. Typically, recirculation of up to 70-80% is required to assure proper S/C (steam to carbon) ratio [2].

Alternatively, if maximization of electrical efficiency is not a priority, the lean fuel can be directly combusted to achieve high thermal power and/or to generate high grade heat available for hot water preparation. Such systems will exhibit relatively high thermal-to-electric ratio (TER), and do not necessarily offer high electrical efficiency.

2. Selected configurations

In recent years several alternative designs were under considerations, including single pass SOFC stacks and systems with recirculation. Current study extends the work previously done by evaluating highly integrated system with two stacks operating in-series. Micro-CHP units constructed in recent years utilize number of advanced components to achieve high electrical and thermal integration. One of the principal methods to substantially increase efficiency is to engage recirculation loop in the anodic compartments of SOFC stacks. Such solution leads to the increase of overall fuel utilization in the electrochemical reaction and supports thermal management of the stack by supplying mixture of fuel delivered from the fuel processor and hot stream of anodic off-gas. This can aid in incorporating fuel processors based on low or intermediate temperature steam reformers, for example bi-functional catalysts for dimethyl ether processing at temperature under 673K.

Recirculation of anodic stream allows to recover steam from the stack outlet and supply it directly to the steam reformer or to the fuel cell stack, if partial internal reforming is considered. Recirculation is however challenging since it requires temperature resistant components or machinery, ejector or recirculation blower, respectively. Additionally certain level of flexibility is needed to allow operation of the overall system in off-design conditions typical for varied electrical loads, transients, start-ups and shutdowns. It has to be mentioned that SOFC stack operating for a long duration will exhibit degradation due to thermal and electrical cycling, typically in the range of 0.5-3.0%/1000 hrs [3]. This is affecting the flow of fuel and oxidant, therefore it has to be taken into account during sizing of components.

In general, ejectors and high temperature blowers offer limited flexibility and are usually considered as components suitable only for steady state operation. Once the recirculation loop is removed from the system, operation in single pass will require continuous delivery of steam to the fuel processor to prevent soot formation and deposition in the fuel line. Depending on the working conditions, type of fuel and the processor, S/C ratios in range 2.0-3.5 are typically needed. In highly integrated system, steam generator can be embedded in the hot box or integrated with anodic lean fuel post-combustor. Optionally, chemically clean water can be recovered from the exhaust line and redirected to the fuel processing unit. Such water-neutral system can be realized using a condensation heat exchanger located in low temperature section of the exhaust system.

3. Modeling methodology

In order to perform steady-state analysis of alternative configurations, simulation platform was developed and implemented in commercial modeling software Aspen HYSYS 8.0. Selected configurations are presented in Fig. 1-2. Main components of systems shown in Fig. 1 and 2 were represented by user-defined models based on dedicated subroutines. Fuel cell stacks were modelled using previously developed numerical tools based on physical properties of fuel cells and the geometry of stack.

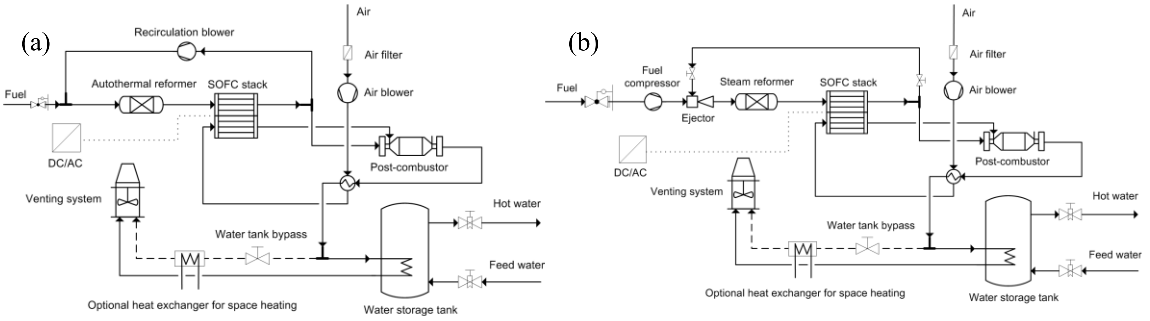

Fig. 1 Scheme of a micro-CHP SOFC-based unit (a) with autothermal reformer , (b) with steam reformer and recirculation of anodic off-gas based on an ejector [4]

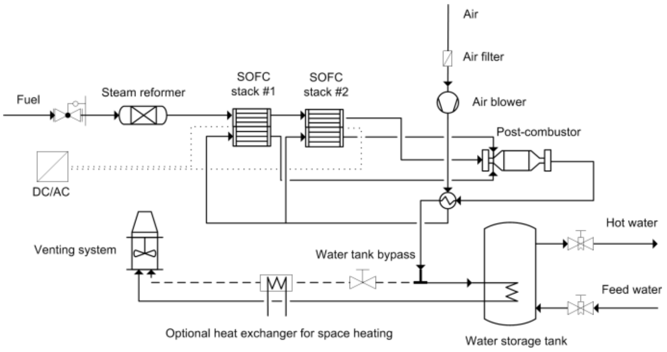

Fig. 2 Scheme of a micro-CHP SOFC-based unit two in-series SOFC stacks

3.1. Model of SOFC stack

Among exiting modeling techniques for SOFC stack, the reduced order model previously proposed [5,6] was adopted to perform current analysis. The method based on electrical circuit equivalent originates from pure mathematical description by Kirchoff's and Ohm's laws described elsewhere [7,8]. Tool was developed especially for system-level studies at sufficiently high fidelity at relatively low prediction errors [9]. With the required level of computational expense, model was implemented in Aspen HYSYS 8.0 modelling platform for simulations of a complete micro-CHP system in several alternative configurations. It should be noted that evaluation of multiple configurations requires reliable modeling method to account for key parameters and assure low computational time with sufficient accuracy. Model exhibits relative prediction error lower than 2.5% and this number was found sufficient for the scope of current analysis. Parameters included in the SOFC model include: (I) active area of a single cell A_{SOFC} [cm^2], (II) number of cells n_{SOFC} [-], (III) thickens of electrodes and electrolyte δ_A, δ_C and δ_E [mm], (IV) ionic and electronic conductivities of SOFC б$_1$ and б$_2$ [S/cm], respectively, (V) minimum inlet temperature to the cathode and anode $T_{C,min}$, $T_{A,min}$ [K], and (VI) maximum core temperature $T_{core,max}$ [K].

Additionally, several parameters of the incoming fuel and oxidant streams were included in the model of a fuel cell stack. Therefore it was possible to account for variations of composition in either streams.

3.2. Models of BoP

The remaining components were represented by corresponding models integrated with simulation platform. Operational characteristics were implemented based on technical and functional specifications of components. Blowers were modelled with performance maps implemented using user defined routines. By this mean it was possible to define isentropic efficiency of machines for different mass flows and pressure ratios. It should be noted, that depending on the configuration of a micro-CHP unit, different sources of pressure drops were present. For that reason operating conditions of blowers vary between the arrangements shown in Fig. 1-3. Model of a high temperature plate fin heat exchanger was previously developed to SOFC-based systems [10] and used in the current study to allow including numerous parameters related to the geometry, working conditions and parameters of corresponding streams. Constant thermal losses equal to 5% of incoming power-in-fuel were assumed. The remaining components were modelled using functional units available in Aspen HYSYS 8.0.

4. Supporting experiments

Series of experiments were performed in order to verify the concept of operating a fuel cell stack on a lean fuel. Therefore, a commercial 1.3 kW SOFC stack has been installed in a dedicated test stand, equipped with anodic and cathodic gas preheaters, mass-flow controllers, electronic load, and data acquisition system. Four thermocouples (type N) installed in the stack core, have been used for stack temperature monitoring. During the experiments, operational temperature in the stack core has been maintained between 1023 and 1133 K except of start-up and cool-down procedures. Fuel and oxidant utilization were equal to 80% and 30% respectively and the total fuel flow has been set to 2 Nm^3/h. The stack comprised 60 cells divided into six 10-cell sections for voltage monitoring. Operating conditions for the experiment have been defined by the numerical model of a system with two SOFC stacks connected in series. The goal was to experimentally validate the possibility of operating the second SOFC stack on the anodic off-gas from the first unit, as well as to examine its performance in lean fuel conditions. Among defined operational points, three cases related to various fuel utilizations in the first SOFC stack were considered. Because molar (and volumetric) flow of the anodic gas does not change during the reaction, the only variable was the hydrogen equivalent of the input gas, equal to molar flow of hydrogen in the H_2/N_2 mixture. A map of stack operation temperatures and power points are presented in Fig. 4 with respect to the hydrogen equivalent of the fuel gas (inlet of the second stack). The highest power equal to 970 W was obtained with 40% H_2 in fuel mixture. In this point, the gas composition was identical to manufacturer's design point for maximum performance but anodic flow was equal to 2 Nm^3/h and temperature was maintained as low as possible taking into account allowable stack voltage drop. In comparison, increasing stack temperature by air preheating allowed achieving 1041 W with the same fuel flow. Lowest investigated H_2 equivalent was equal to 20 mol/h corresponding to higher fuel utilization in the first SOFC stack. In this case power of 602 W was obtained with stack core temperature ca. 50 K lower than for highly energetic fuel. In Fig. 4 it can be observed that predictions of the model are in agreement with data collected during experimental investigation of the stacks. In fact the model's underestimation is equal to 4.43% based on average relative prediction error.

The results indicate that the operation of two SOFC stacks connected in series (anode flow) is possible and gives opportunity to reach very high fuel utilization (>90%) [11].

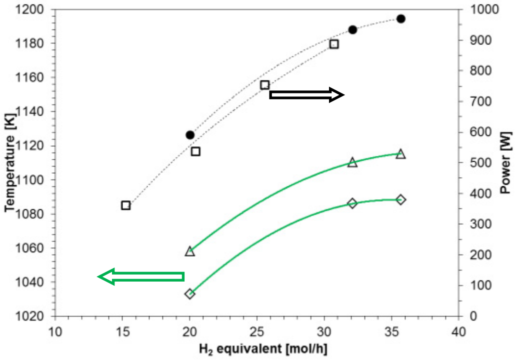

Fig. 4. Map of SOFC stack core temperature (minimum ◇ to maximum △) and stack power points (●) for SOFC stack operating point: U_{ox} = 30%, U_f = 80%, total anode flow = 2 Nm^3/h; stack voltage maintained above 6 V/10 cells in each block. Stack power obtained from the model of the second SOFC stack operating at U_{ox} = 30%, U_f = 80% are presented (☐) in a range of operating conditions defined by the first stack.

5. Results obtained from the models

Comparative analysis of selected configurations was done using numerical simulator built for evaluation of alternative outlines of the system. Technical and operational constraints were based either on components specifications or theoretical calculations. General concept of connecting two identical SOFC stack in-series was experimentally verified. In order to evaluate the systems, performance maps were built for selected operating modes. Examples of maps obtained from the numerical simulator are shown in Fig. 6. Each map is constructed using 440 sets of results obtained from fully converged simulation for particular working conditions. The net efficiency of stand-alone two stacks in series can be seen in Fig. 6a, while overall electrical efficiency of the system is shown in Fig. 6b.

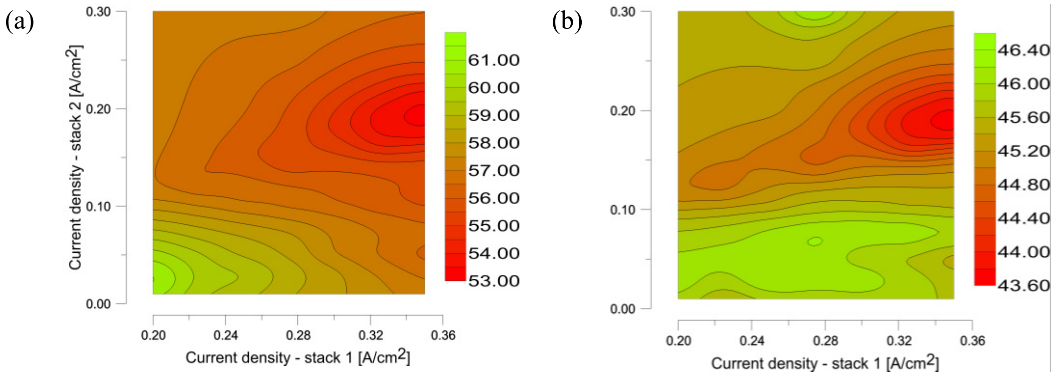

Fig.6 Performance maps obtained from the numerical simulator for a micro-CHP unit with two SOFC stacks in-series (a) net efficiency of two stand-alone SOFC stacks, (b) electrical efficiency of complete system.

6. Conclusions

Connection of fuel cell stacks in series offers high electrical efficiency without engaging advanced recirculation machines or devices. Use of two fuel cell stacks within one power unit enables operational flexibility, not available for systems with recirculation loop.

With two stacks in series, the first stack operates as a primary electrical generator and second unit, operating at relatively low current, typically under 0.2 A/cm^2 can be used to boost the electrical efficiency. Work done by Schimanke et al. [12] proved that combination of two stack in series enable increase of efficiency from 40 to 50% for a system with combination of CPOX and SR within the unit fed by methane. Similar results were achieved in the current study.

It was found that electrical efficiency of the system with two in-series SOFC stacks is higher by 3-7 %-points in comparison with systems based on parallel connection of two stacks. Experimental studies were performed to verify the possibility of operating SOFC stack in series at desired conditions. Demonstration system with two stacks is currently under construction, and preliminary testing will be done to verify the concept at the system-level.

Acknowledgements

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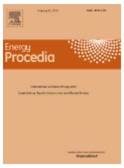

Biography

Dr. Jakub Kupecki works as a Research Fellow in Thermal Processes Department, Institute of Power Engineering (IEN). He published more than 20 papers, chapters and book on fuel cells. Currently, Dr. Kupecki is leading at IEN two large EU projects related to field demonstration of fuel cell technology.