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Experimental and numerical analysis of a serial connection of two SOFC stacks in a micro-CHP system fed by biogas

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ABSTRACT

This paper presents the results of an evaluation of a conceptual micro-CHP unit with two serially connected integrated stack modules (ISM), each made up of two 30 SOFC cells packages. In-series connection of two identical commercial 60-cell stacks with electrolyte-supported SOFC was under evaluation. In order to achieve high overall fuel utilization in the system which enables achieving high electrical efficiency, the concept was analyzed with respect to the operational regimes typical for a commercial SOFC stack. Numerical analysis included simulation of the complete system, including fuel processor, SOFC stacks and BoP components. Additionally, an experimental setup with a commercial 1300 W SOFC stack was used to reproduce operating conditions obtained from the model. Validation of the concept was necessary to qualitatively and quantitatively determine the possibility of operating a second stack on a lean fuel originating from the anodic compartments of the first stack. Results of the analysis presented in the paper were used to aid in defining the optimal outline of a micro-CHP power system, constructed at the Institute of Power Engineering (IEN). Predictions of the models were in agreement with preliminary experiments, proving that the concept of the in-series stacks configuration is 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 under conservative assumptions.

Introduction

Several alternative designs of efficient power generators with solid oxide fuel cells (SOFC) 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. A hybrid combining the SOFC and Stirling engine can be realized for 10 kW-range power systems [1].

In selected power units alternative solutions such as simultaneous hot utility water preparation and space heating can be applied. To benefit from the high electrical efficiency of the direct electrochemical oxidation of a fuel in fuel cells, optimal designs of micro-power units are sought.

While a solid oxide fuel cell stack is highly efficient, it does not completely utilize the fuel. For that reason different solutions are considered with the aim being to achieve high overall fuel utilization, including recirculation of depleted anodic fuel with blowers or ejectors [2]. Typically,

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recirculation of up to 70–80% is required to assure proper S/C (steam to carbon) ratio [3]. A system of this type was subject to consideration in an earlier study [4]. Recirculation of hot gases exiting the anode can be done either with a high temperature blower or ejector. The former solution offers significant advantages over the latter, but the cost of the additional, advanced machine or device might substantially increase the CAPEX of the system. On the other hand, application of an ejector results in a durable solution but with very limited operational flexibility. Moreover, the ejector requires elevated pressure at the feed site to make the recirculation of gases possible. Both discussed units make it possible to achieve high electrical efficiency, which can be maintained while operating in the design point.

Alternatively, if maximization of the electrical efficiency is not a priority, the lean fuel can be directly combusted to achieve high thermal power. Such systems will exhibit relatively high thermal-to-electric ratio (TER), but do not necessarily offer high electrical efficiency. To overcome the disadvantages of systems with recirculation, a system with two identical stacks connected in series is proposed. The concept was investigated numerically and validated experimentally.

In recent years several alternative designs of micro-CHP units with solid oxide fuel cells were investigated. Studies included single-pass SOFC stacks and systems with recirculation. Several alternative systems were selected for field tests and are reported in the literature. Freese and Fenema [5] reported a field test of available micro-CHP units based on SOFC in Dutch households. The tested units were equipped with data acquisition devices for thermal and electric output of devices as well as outdoor temperature. Promising results of the field test justify the SOFC technology as suitable for European households. Manning et el. [6] performed field tests of four different micro-CHP systems in a special twin house facility developed for experimental evaluation of micro-CHP systems in real conditions. A prototype tubular SOFC system was installed and operated. The results, compared to commercial Stirling engine- and two alternative internal combustion engine-based systems, allowed for assessment of needed improvements to the micro-CHP-SOFC technology, which are necessary for the purpose of bringing it closer to the market. A decade ago, Bell et al. [7] demonstrated a tubular-SOFC based, laboratory 5 kW micro-CHP system prototype. The LHV-based DC electrical efficiency was 46.6% in a test over 1600 h long. The authors demonstrated the possibility of installing a micro-CHP-SOFC system in a single family house, meeting electrical needs and decreasing peak load of the house. Additionally significant export of electricity to the grid during the test was reported. Within the framework of the European project FC-DISTRICT a planar SOFC-based micro-CHP system was designed to operate in an intelligent network of buildings interconnected by a local district-heating network [8]. The SOFC micro-CHP system in the project was based on a commercial SOFC stack from the same supplier (Staxera) as the one used in the current study. Within the project, the stack manufacturer improved and tested the thermal and redox cycling resistance of their stack technology. 150 thermal and 10 redox cycles were demonstrated with a degradation rate less than 0.5% caused by the latter.

Micro-CHP units constructed in recent years utilize a number of advanced components to achieve high electrical and thermal integration. One of the major methods to substantially increase the electrical efficiency is to engage, as mentioned above, a recirculation loop downstream of the anodic compartments of a SOFC stack. This solution leads to increased overall fuel utilization in the electrochemical reaction and supports thermal management of the stack by supplying a mixture of fuel delivered from the fuel processor and a 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 temperatures under 673 K.

Recirculation of the anodic stream allows steam to be recovered from the stack outlet and supplied directly to the steam reformer or to the fuel cell stack, if partial internal reforming is considered. Recirculation is challenging, though, since it requires temperature resistant components or machinery such as an ejector or recirculation blower. Simplified schematic diagrams of a micro-CHP system with a high temperature blower and ejector are shown in Figs. 1 and 2, respectively.

Additionally, a 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 borne in mind that a 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 h [10]. However, Risoe has reported lower degradation rates about 0.1–0.8%/1000 h. As it affects the flow of fuel and oxidant, it has to be taken into account when sizing the components and designing the whole system.

In general, ejectors and high temperature blowers offer limited flexibility and are usually considered as components suitable only for steady state operation with minor variations of the stack load. Once the recirculation loop is removed from the system, operation in single pass requires 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 a range from 2.0 to 3.5 are typically needed. If catalytic partial oxidation (CPO or CPOX) is engaged in the system, the S/C ratio can be maintained at lower values compared to autothermal steam reforming (ATR). In a highly integrated system, the steam generator can be embedded in the hot box or integrated with an anodic lean fuel post-combustor. Optionally, chemically clean water can be recovered from the exhaust line and redirected to the fuel processing unit. A water-neutral system can be realized using a condensation heat exchanger located in a low temperature section of the exhaust system.

In-series connection of SOFC stacks

A single fuel cell operating under current load in a high fuel utilization regime is subjected to activation, ohmic and concentration losses resulting in a drop of operational voltage. The solid oxide fuel cells and stacks show a decreased lifetime in the case of a higher cell polarization operation. Therefore, minimum voltage-per-cell limits must be kept to increase the

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