PUBLICATION [P2]

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In: ECS Transactions 35 (1), pp. 113-120

ECS Transactions, 35 (1) 113-120 (2011)
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Performance of a 10 kW SOFC Demonstration Unit

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Experimental results of the performance of a solid oxide fuel cell (SOFC) unit are presented. The unit was designed, manufactured and tested at the VTT Technical Research Centre of Finland. The 10 kW power class SOFC stack and stack module were designed and manufactured by Versa Power Systems (VPS). A successful commissioning test of the unit was conducted in 2010. Long term testing of the unit was started in November 2010. The unit has been operated with natural gas for over 1500 hours supplying electricity to the local grid. The unit has shown robust and uninterrupted performance. Stack DC efficiency of 60% and system net AC efficiency of 43% has been measured during the operation.

Introduction

The high electrical efficiency obtained with SOFC-based power plants is the key benefit of the SOFC technology when competing in the power production market against conventional production technologies. However, a sufficiently long lifetime of both the SOFC stacks, as well as the necessary Balance of Plant (BoP) components, is an essential condition for the commercialization of SOFC power plants. With no large-scale production of such plants, the lifetime and performance of different system components as well as the SOFC stacks operated at in-system conditions are currently not well established. Furthermore, building large 100 kW to MW range SOFC power systems requires developing large-size SOFC stacks as well as developing the techniques for integrating such stacks with the BoP components. In order to assess the multiple technical challenges related to such SOFC power plants, it is necessary to design, build and experiment on complete SOFC demonstration systems. This paper presents the experimental results of the performance of such a SOFC demonstration unit.

Experimental

The aim of the system design was to realize a grid-connected, single stack SOFC system with a high electrical efficiency while having no external steam or heat supplied to the system. The targeted stack DC-efficiency and system net AC-efficiency at the nominal operating point were 60% and 50%, respectively. The system was designed around a 10 kW planar SOFC stack produced by VPS. An anode recycle loop was included to enable water independent operation for the fuel system. The unit consists of two interconnected modules, the balance of plant (BoP) and the stack module (1). A power conversion unit converts the stack DC power to AC power and supplies it to the electric grid (2,3). A simplified process flow chart is shown in Figure 1 and a picture of the complete system in Figure 2.

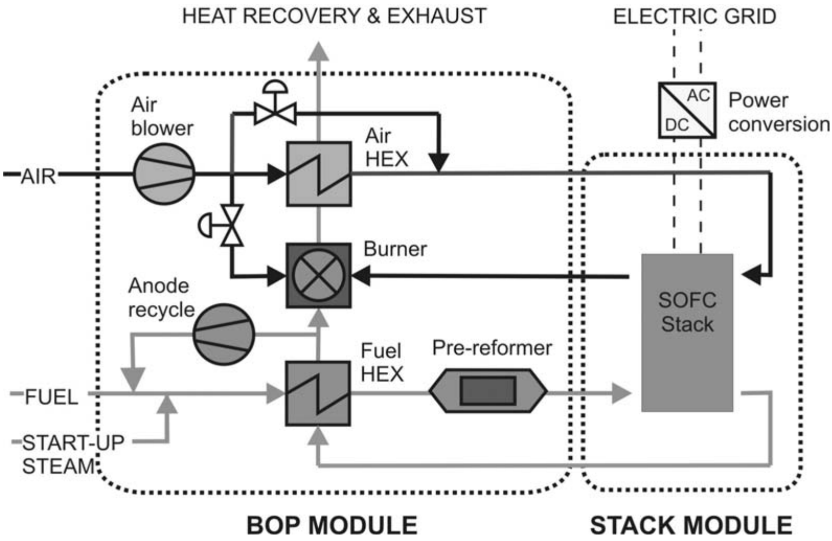

Figure 1. Simplified process flow diagram of the SOFC demonstration unit.

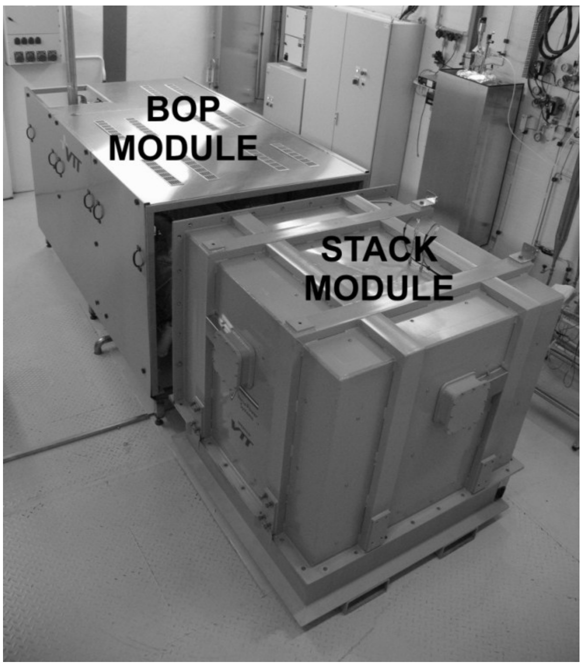

Figure 2. 10 kW SOFC demonstration unit. Physical dimensions are ca. 4 m x 1.5 m x 1.5 m (L x W x H).

The stack module contains the stack and its compression system, thermal insulation, electrical start-up heater and stack-related instrumentation. The stack consists of 64 anode-supported cells each having an active area of 550 cm^2. The internal flow configuration of the stack is cross-flow. The cathode inlet is open to the module internals, and therefore, the inlet air circulates inside the module before entering the stack.

The BoP-module contains the air and fuel processing systems. An air blower draws ambient air into the system and feeds the main flow through a heat exchanger and further into the stack module where it enters the stack cathode. From the cathode, the exhaust air is fed to a catalytic burner which helps in preheating the cathode inlet air. Through a control valve, the air blower also supplies additional cold air to the burner when necessary to prevent it from overheating. Part of the incoming fresh air can also be fed through a heat exchanger by-pass line. This by-pass can be tuned to achieve the desired thermal operating point for the stack. Thermal insulation of the BoP-module is such that all the components and pipelines are independently insulated.

The natural gas fed in to the fuel system is mixed with the recycled anode exhaust gas and heated in the fuel heat exchanger before passing it to the pre-reformer. The pre-reformer is based on a commercial noble metal catalyst. After the pre-reformer, the fuel enters the stack module and reacts in the stack anode. Approximately 12% of the methane present in the fuel is reformed in the pre-reformer. The rest is carried on to the stack, where it is reformed internally. The anode exhaust gas is fed through the heat exchanger to pre-heat the fresh fuel. An anode gas recycle blower draws part of the anode exhaust gas back to the fresh fuel side of the heat exchanger. The rest of the fuel is fed to a catalytic burner to help pre-heat the air.

The unit is designed for unattended operation, and for this purpose a control system has been implemented in an industrial PLC environment. The primary reference variable for the overall system control is the stack DC current, which is set by the system operator. A variety of closed- and open-loop controls are utilized to achieve automated operation and to keep the stack and BoP –components within predefined operating boundaries. Safety logics have been implemented within the control system that monitors the critical process parameters and initiates various levels of shutdown sequences if needed.

Results

Overview of the Test Runs

A successful commissioning test of the demo unit was conducted in April through June 2010 to validate the system design, layout and controls. For this purpose, a previously used stack that had already reached its end-of-life voltage was used. In total, approximately 1000 hours of operation was accumulated during commissioning, and current was drawn from the stack for 720 hours. Thermally self-sustained operation i.e. electric heaters off, as well as water independent operation via anode gas recycle alone i.e. external steam supply off, was accomplished. The control system worked reliably for the entire duration of the commissioning test demonstrating stable and robust operation of the unit. (1)

A long term test with a new stack with beginning-of-life voltage was started in November 2010. The purpose of the long term testing is to optimize the operating conditions to yield maximum electrical efficiency and to study the durability of the SOFC stack and the BoP –components. As of January 4, 2011, the unit has been operated for over 1500 hours. Operation of the unit has been robust with no control disturbances or component failures (Figure 3).

The test run was initiated by heating the system with electric heaters up to operating temperature while flushing the fuel system and stack anode with a hydrogen-nitrogen purge gas mixture. Once the operating temperature was reached the natural gas supply and start-up steam supply were started and the stack current was ramped up to 135 A with 5 A min^{-1}. During the first 500 hours of the test, the unit was operated with varying stack current to measure the part-load operating characteristics of the stack and the BoP-components. The nominal operating point of 200 A stack current, 20% air utilization and 80% system fuel utilization was reached at 505 hours after the test start. At stack currents in excess of 115 A, the unit has relied only on anode gas recycle and no additional steam has been fed to the system. Thermally self-sustained operation with the electric start-up heater switched off was achieved with a stack current of 160 A or higher. With a lower stack current (135-160 A) the start-up heater power ranged from 150 to 400 W.

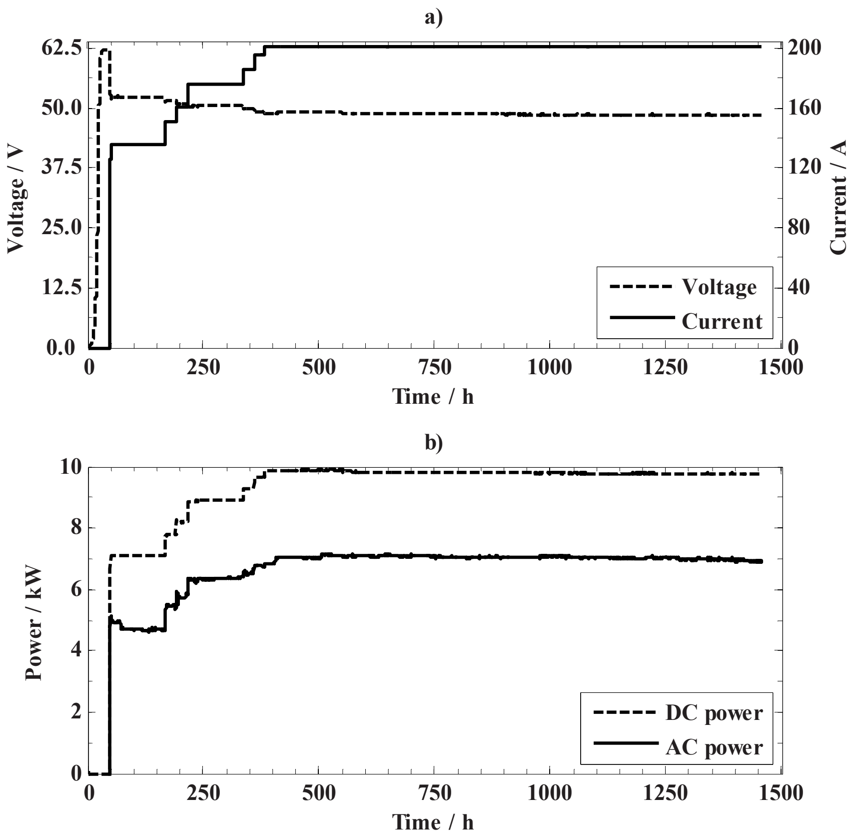

Figure 3. a) DC current and voltage of the SOFC stack and b) the stack DC and unit net AC power output to the grid during the test.

System Performance at Nominal Operating Conditions

At nominal operating conditions, the stack DC efficiency was 60%, based on the lower heating value of natural gas, and DC power output was 9.8 kW. Due to parasitic power consumption of the air and recycle blowers, and the losses in the current collection and DC-AC power conversion, the resulting power output to the electric grid was lower (Figure 4). The net AC efficiency was 43% and the electric power output to the grid was 7.1 kW.

The overall design target of 50% net AC efficiency was not reached due to higher losses than anticipated e.g. in the DC current collection cabling and in the power conversion equipment. However, it is possible to significantly cut down the current collection losses by shortening the current cables and by reducing both bulk resistivity and the contact losses in the hot environment of the stack module as well as the contact losses at several locations in the ambient environment. Furthermore, the power conversion unit (PCU) used for the test run has an overall efficiency of 88%, which is lower than the projected final design value (>90%). By decreasing the current collection losses from 470 W to 150 W, and by increasing the PCU efficiency from 88% to 92%, the net AC efficiency could be improved up to 47%.

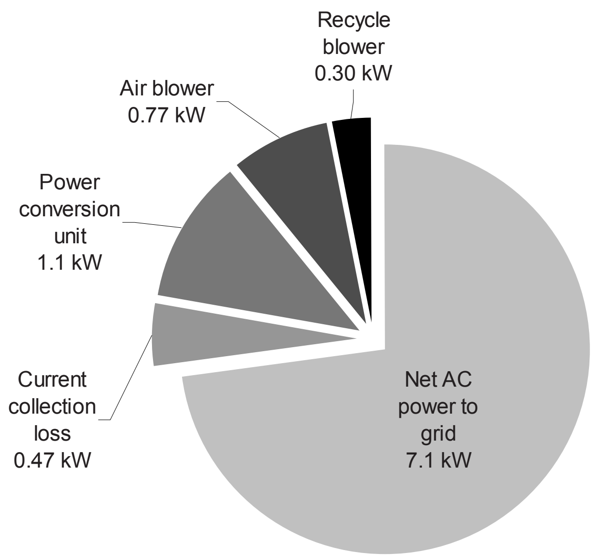

Figure 4. Power conversion and parasitic losses from the stack DC-power (9.8 kW) at nominal operating conditions.

System Performance at Part-load

Operating under partial load generally decreases the system efficiency. Demonstrated part-load operating characteristics and the effect of system controls to the unit and stack efficiency are depicted in Figure 5. It can be seen that though the stack voltage is higher when less current is drawn from the stack (Fig. 5a), the part-load operation results in decreased efficiency of both the stack and the system (Fig. 5b). This is because lower system fuel utilization rate is used at part load (Fig. 5c) in order to increase the operating temperature of the catalytic burner. Higher burner temperature provides more efficient cathode air pre-heating, and increases the stack module air inlet temperature. (Fig. 5d). At part-load, less heat is generated in the stack proportionally to the heat losses, and higher stack module air inlet temperature is beneficial to maintain thermally self-sustained operation.

Part load efficiency of the system has not yet been optimized, and electrical efficiency could likely be improved by making adjustments to increase system fuel utilization and decrease cathode air flow at part load.

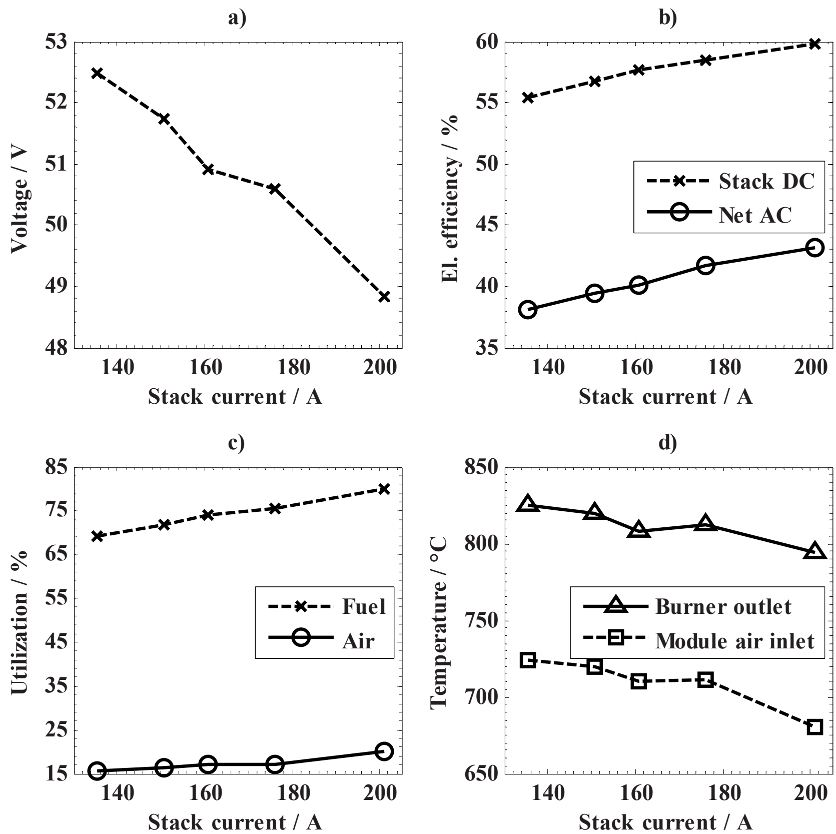

Figure 5. Performance of the unit at part-load. a) Stack voltage, b) DC efficiency of the stack and system net AC efficiency, c) System fuel utilization and air utilization, and d) Stack module air inlet temperature and burner outlet temperature.

Sensitivity to Process Parameters

In order to achieve higher system electrical efficiency, a series of experiments were conducted to investigate the effect of different process control parameters to the power output and electrical efficiency. The control parameters under investigation were the system fuel utilization, recycle ratio and air utilization, where the flow rates of natural gas, recycle gas and cathode air were varied, respectively. To examine the effect of air utilization, the cathode air flow rate was varied between 1060 and 1250 l_N min^{-1}, corresponding to air utilization rates between of 17% and 20%, respectively. The stack current was kept constant at 200 A and the system fuel utilization rate at 80%. The experiment results are depicted in Figure 6.

Due to back-pressure characteristics of the system components and the operational characteristics of the air blower, the parasitic power consumption of the blower was decreased 1025 W to 790 W by lowering the air flow rate. Concurrently the stack voltage was increased by 0.2 V (~3 mV/cell) with smaller air flow rate, due to slightly increased stack temperature. However, the parasitic power consumption of the blower dominates the overall effect on the power output and efficiency (Figure 6). The net AC power output and the net AC electrical efficiency increased by 270 W and 1.6 %-units, respectively.

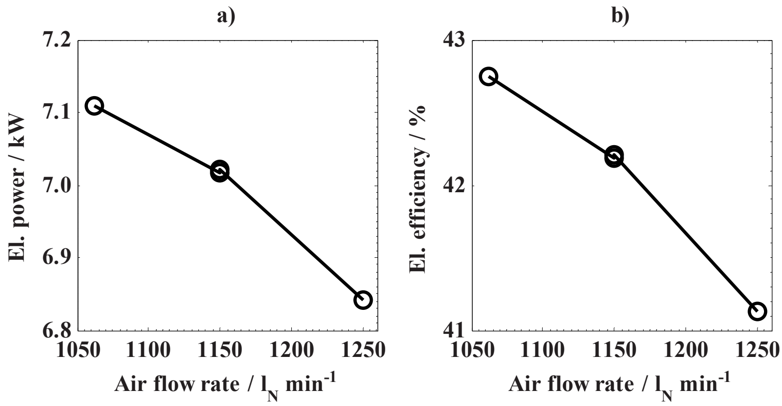

Figure 6. Effect of air flow rate to the a) net AC power output to the grid and b) net AC efficiency. Stack current = 200 A, System fuel utilization = 80%.

Conclusions and Future Work

The SOFC demo unit has been tested successfully at nominal operating conditions as well as under partial load. A DC power output of 9.8 kW with 60% gross DC efficiency was achieved for the SOFC stack. The corresponding values for the unit net AC power and efficiency were 7.1 kW and 43%, respectively. Operation of the unit has been robust for over 1500 hours without any control disturbances or component failures. The effects of several process parameters were investigated to optimize the electrical efficiency and power output of the unit. The experiments have proceeded to long-term testing where the purpose is to study the durability of the SOFC stack and the BoP –components during operation over several thousands of hours.

Acknowledgments

Funding for this study was obtained through the SofcPower project. The Finnish Funding Agency for Technology and Innovation in Finland (TEKES) as well as the companies participating in the project are gratefully acknowledged for their financial support. Project partners from the Lappeenranta University of Technology (LUT) are acknowledged for the design, manufacturing and testing of the power conversion unit. The Aalto University Department of Engineering Design and Production is acknowledged for their participation in the mechanical design of the BoP-module. Mr. Kari Koskela and Mr. Kai Nurminen from VTT are thanked for their contribution in the construction of the demo unit.

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