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Experimental Investigation of Peripheral Components in a SOFC/Gas Turbine Hybrid Power Plant

Mike Steilen, Christian Schnegelberger, Moritz Henke, Caroline Willich, Josef Kallo, K. Andreas Friedrich
German Aerospace Center (DLR), Institute of Engineering Thermodynamics
Pfaffenwaldring 38-40, 70569 Stuttgart, Germany
Tel.: +49-711-6862-8039
mike.steilen@dlr.de

Abstract

Solid Oxide Fuel Cells (SOFC) and gas turbines (GT) can be directly coupled to form efficient hybrid power plants providing electricity based on various fuels. The operation of such a hybrid power plant theoretically allows for electrical efficiencies in the range of 70 %. To ensure stable and efficient system operation the different operating characteristics of the major components SOFC and gas turbine as well as other factors like fuel type etc. require careful consideration of component design and operating strategy.

The DLR undertakes efforts to erect and operate a pilot hybrid power plant in the range of 30 kW of electrical power. Technical feasibility is to be demonstrated and the operating and design parameters for proper system operation are to be determined. The SOFC temperature management and the system pressure management are considered most important from SOFC perspective.

The temperature management can be supported by anode gas recirculation and, if hydrocarbons are utilized as fuel, by the mainly endothermic reforming reactions. A test rig was set up at the DLR to analyze the effects of pressure and flow speed on reforming reactions prior to the SOFC. A second test rig is used to characterize commercially available ejectors at high entrainment rates to potentially enlarge the operating range of the hybrid power plant.

This paper will be focusing on the differential pressure test since so far only limited information has been available on maximum differential pressures between SOFC anode and cathode. Therefore, a differential pressure test rig was set up at the DLR to determine the capabilities of the stacks to be used in the pilot power plant.

The experimental results are summarized in an overview to be discussed during the presentation.

Introduction

The major idea of the SOFC/GT hybrid power plant is to improve overall conversion efficiency from chemical energy to electric energy. There is a significant amount of thermal energy left in the SOFC exhaust gas due to typical SOFC operating temperatures above 800 °C. Furthermore, there is some chemical energy left in the SOFC exhaust gas due to the excess fuel required to avoid local fuel starvation.

The high temperature cathode and anode exhaust gasses are mixed in a combustion chamber to supply heat to drive a turbine. The turbine propels the air compressor and an electric generator. The primary effect of SOFC exhaust gas enthalpy utilization is flanked by the secondary effect of SOFC pressurization. Gas turbine operation requires heat and pressure differences along the turbine and delivers compressed air through the compressor. In turn, the compressed air is used in the fuel cell process as well as for SOFC temperature management. The SOFC efficiency is improved due to pressurized operation [1] and thus this secondary effect is activated.

The general concept introduced above is set up in a pilot power plant and thus comes along with some practical restrictions. The pilot power plant is to be operated with natural gas and therefore a reformation process has to be considered for SOFC operation. The concept chosen for natural gas reformation is the steam methane reforming (SMR) process in which a source for steam is required. The SOFC reaction product is water at SOFC operating temperature, so that an anode recirculation can provide for required steam. While on anode side a fuel compressor and a recirculation device is included in the cycle, the cathode side is affected by the air compressor integrated in the gas turbine as shown in Figure 1. The different components and potential interactions between anode and cathode side will induce pressure differences in operation.

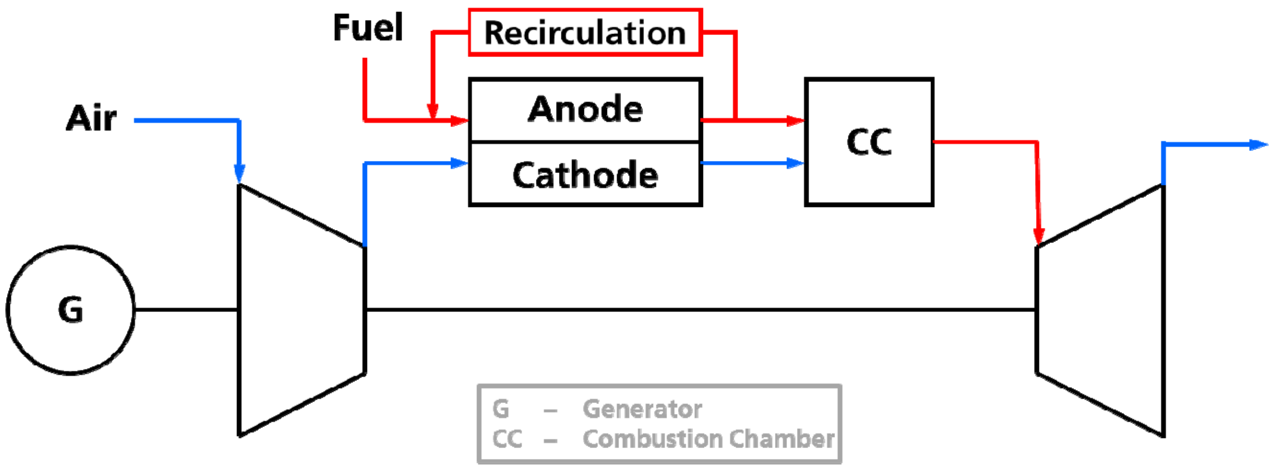

Figure 1: SOFC/GT Hybrid Power Plant General Layout

The effects of pressure differences on SOFC stacks are evaluated experimentally; the related test procedures are explained and potential failure mechanisms are identified. Finally, the following tasks are outlined.

1. Scientific Approach

Manufacturer specifications on differential pressures between anode and cathode typically range in the area of a few kPa. An arbitrary gas turbine test cycle shows pressure changes at the compressor outlet in the range of about 10 to 20 kPa/s as illustrated by Figure 2. A pressure change on cathode side induces a differential pressure between anode and cathode since the fuel pressure is externally controlled and might have insufficient reaction time. The gas turbine chart is recorded during an arbitrary test cycle with the MTT EnerTwin gas turbine that is part of the pilot hybrid power plant project. This turbine is eventually coupled with the SOFC to form the pilot power plant. The origin and potential control of the pressure changes is addressed and evaluated within the DLR Institute of Combustion Technology which is partner in this project.

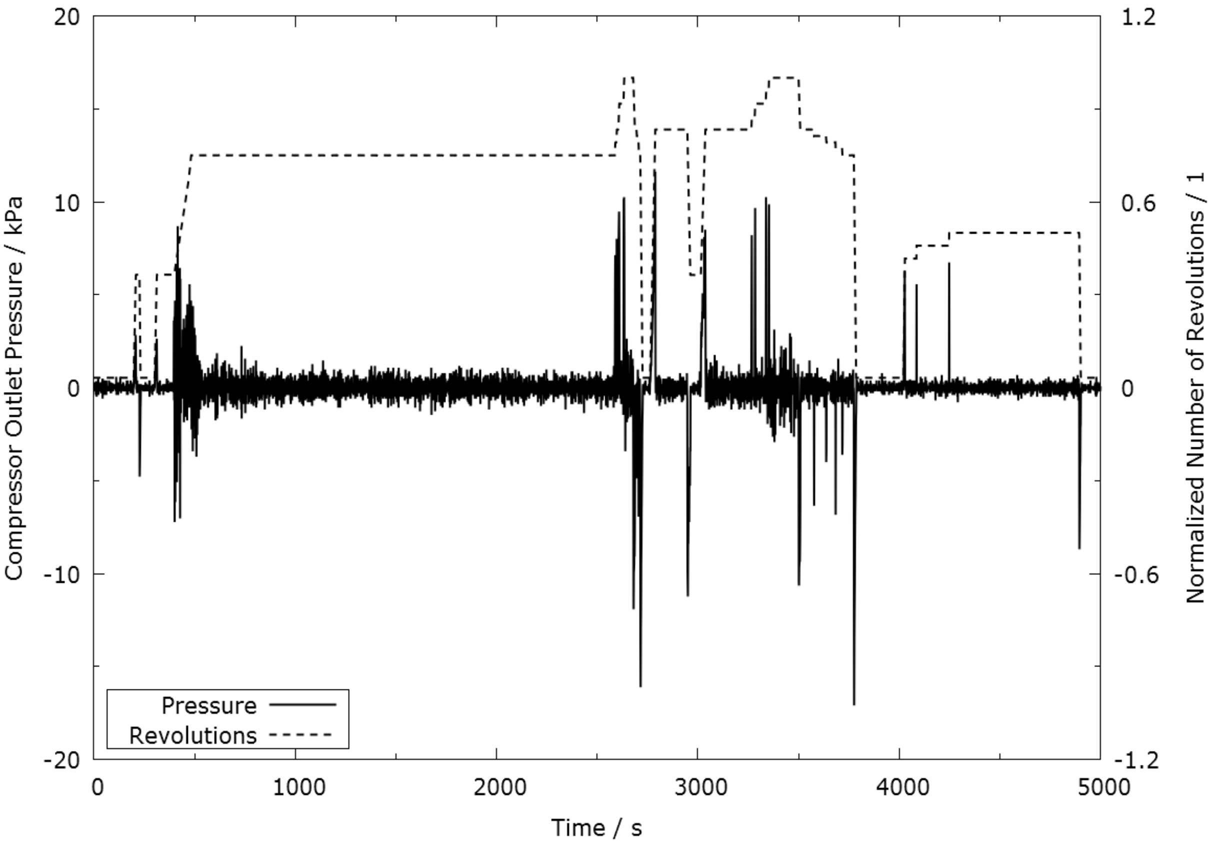

Figure 2: Compressor Outlet Pressure, Sample Time 1 Hz.

There are very limited applications were pressurized SOFCs are in operation and experience on differential pressures between anode and cathode are either very limited or unpublished. Thus, on the SOFC side of the project the maximum differential pressure is evaluated with destructive testing of short stacks. The test procedure is developed; the test rig is set up and tailor-made specimens are designed to account for the requirements of the project. The tests are carried out and finally, post mortem analyses are performed to identify potential failure mechanisms. Potential failure mechanisms to be expected are seal failure or electrolyte failure, both failures related to mechanical integrity. Here, the details of the test procedure, the test results and the potential failure mechanisms are shown and discussed while the test rig and test details are shown with contribution A1212 in EFCF 2014.

2. Experiments

The target of the experiments is to find the mechanical integrity limits of the stacks with pressure differences to identify potential failure mechanisms. The destructive experiments are planned stepwise. Stationary as well as transient tests are performed while each test type is carried out several times with different stacks. The test stacks are disassembled and post mortem analyses are carried out afterwards. Both test types are performed with anode overpressure as well as cathode overpressure to account for the pressure difference situation according to Figure 2. Since the cell design does not allow for clear separation of electrolyte failure or sealing failure additional tests are performed with a sheet metal replacement instead of the electrolyte. Another test type is based on the variation of compression force to investigate the related effect on the glass seal.

The stationary test procedure incorporates pressure changes over time which are carried out very slowly and in a stepwise manner to minimize fluctuating effects and drifts. Therefore, the test is virtually stationary as illustrated in Figure 3.

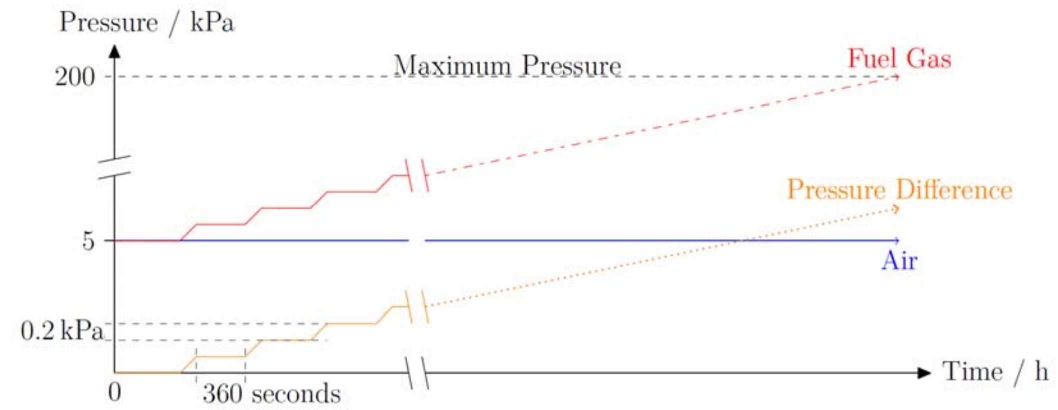

Figure 3: Stationary differential pressure test schematic.

The gradient tests are based on the results from the stationary tests. The maximum differential pressure level for the gradient tests is chosen far below the stationary results. The chosen maximum differential pressure level is approached with a moderate gradient, followed by steeper gradients until stack failure occurs as illustrated in Figure 4. If the stack withstands the final instantaneous pressure increase the chosen pressure level is increased and the gradient test procedure is repeated.

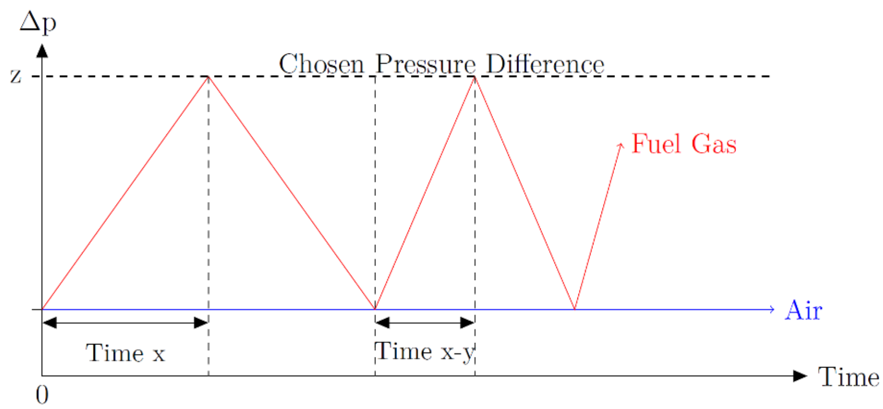

Figure 4: Gradient differential pressure test schematic.

All tests are performed in a furnace at SOFC operating temperature of about 1123 K. A gas pre-heating device is included to avoid thermo-mechanical stress within the stack. The cathode flow medium is air whereas forming gas (95 mol/mol N_2, 5 mol/mol H_2) is used on the anode side to avoid any effects related to anode oxidation. The open circuit voltage (OCV) is monitored during the tests as well. The test rig is equipped with backpressure control as shown in detail in contribution A1212 in EFCF 2014.

Due to the open cathode stack design, a gas tight metal housing is designed around the stack to allow for cathode pressure control. This tailor-made specimen design enables the use of a standard chamber furnace without furnace pressure control.

Prior to any experiment, each specimen is tested for leakage to ensure a gas tight housing and to prove correct function of the glass seals and mechanical integrity of the electrolyte.

3. Results

As of May 2014, 14 stationary tests have been carried out as shown in Figure 5. While three tests could not be finished due to issues with the test rig and potential handling and transport failures eleven stationary test results are achieved. A large spread of results which is independent from test direction can be seen. The manufacturer specification is a maximum of 3 kPa of differential pressure, thus all valid results comply with this specification.

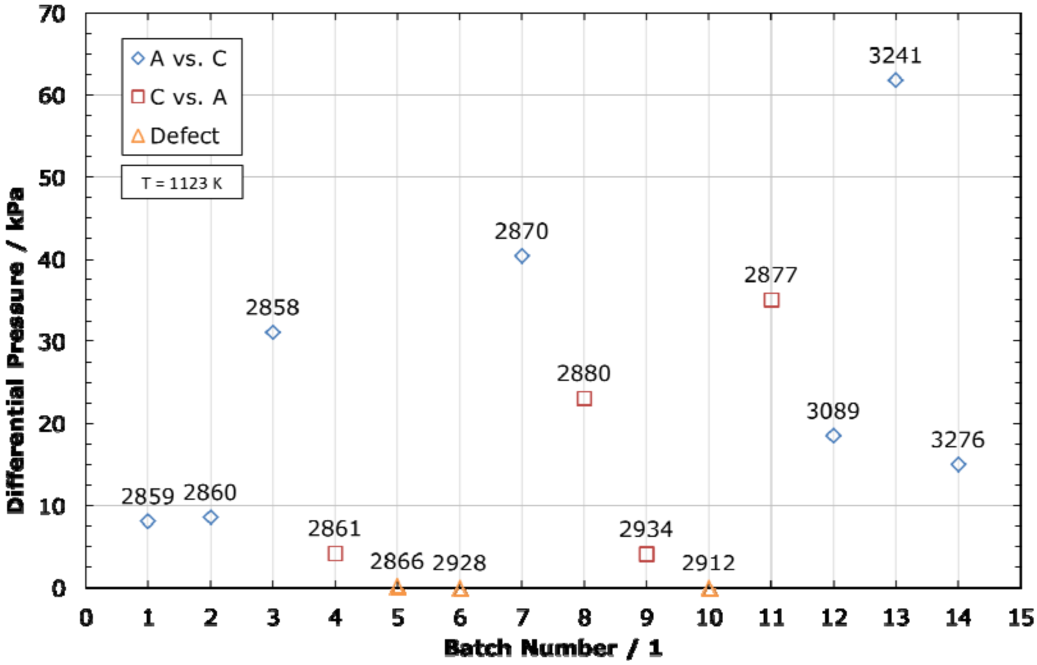

Figure 5: Stationary test results with stack serial numbers for anode (A vs. C) and cathode (C vs. A) overpressure.

There is little sense in starting the gradient tests while the stationary results differ that much. The governing effects in a gradient test cannot be identified while even the stationary results are unclear. Therefore, the failure mechanisms governing the stationary tests have to be identified first to reduce the result spread for future tests.

The post mortem analyses (PMA) of all stacks indicate glass sealing failure as single failure mechanism. None of the PMAs indicate electrolyte failure. The indications are independent from test direction; analogical results are obtained for anode overpressure (A vs. C) and cathode overpressure (C vs. A). An example for glass seal failure in each direction is given in Figure 6.

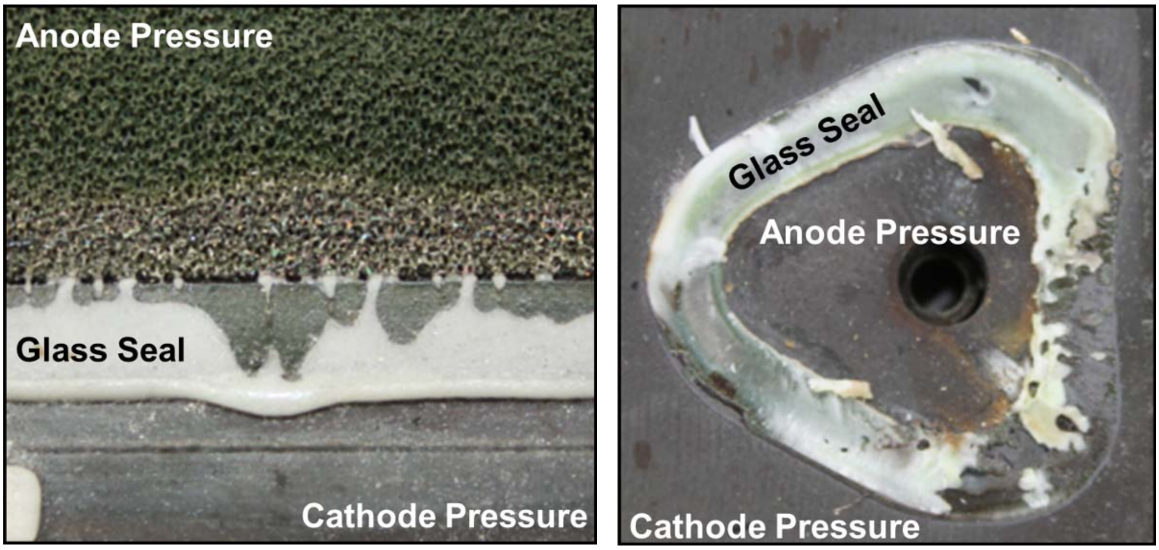

Figure 6: Magnified pictures showing affected glass seals after tests
Left: Anode overpressure, Serial No. 2858, Δp_{max} = 31 kPa,
Right: Cathode overpressure, Serial No. 2880, Δp_{max} = 23 kPa.

4. Conclusions

The manufacturer specification of 3 kPa pressure difference is exceeded with all stationary test results if the stack is not damaged beforehand. The stationary tests show a significant spread of results, thus the transient tests require a design improvement prior to test start. The spread of results covers the required range above 20 kPa as well as the insufficient range below 10 kPa.

The identified failure mechanism is loss of glass seal integrity. No indication related to electrolyte failure is found.

5. Prospects

The glass seal performance is to be stabilized in the required range above 20 kPa to fulfill the pilot hybrid power plant requirements. Stable glass seal performance is mandatory to start the succeeding transient tests and to evaluate the effect of compression force variation.

References

[1] Moritz Henke et al., Effect of pressure variation on power density and efficiency of solid oxide fuel cells, Electrochimica Acta, Volume 66, 1 April 2012, Pages 158-163, ISSN 0013-4686, http://dx.doi.org/10.1016/j.electacta.2012.01.075.