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Turbocharged SOFC System: Emulation and Control in Cyber-Physical Mode

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Abstract. The objective of this work regards an SOFC system pressurized by a turbocharger and the related emulation tests for control system development. Due to the interest in coupling high efficiency operations with reasonable capital costs a turbocharged SOFC plant layout has been proposed. This is due to significant cost decrease (in comparison with microturbine-based SOFC hybrids) related to the application of a turbocharger based on large mass manufacturing process. Moreover, the system has been sized to work with biogas to operate with a renewable source.

Due to the difficulties in studying the SOFC/turbocharger integration, especially for the dynamic and control aspects, the University of Genoa developed a devoted test rig where the fuel cell is emulated with a pressure vessel equipped with a burner (to have the same temperature range) and inert ceramic material (to have the same time-dependent response). The emulation tests presented in this work have been carried out to demonstrate the system feasibility in dynamic conditions and to assess the control system performance.

1 Introduction

The necessity of reducing emissions of pollutants and greenhouse gases is shifting the attention of the power generation sector towards innovative technologies, such as fuel cells. Among the different types of fuel cells, Solid Oxide Fuel Cells (SOFCs) have emerged as a particularly promising solution due to their high efficiency, low emissions, and fuel flexibility [1]. Moreover, the high energy content of their exhaust gases makes it possible to integrate the SOFC stack with turbomachinery, typically micro gas turbines (MGTs), resulting in a higher system efficiency [2].

In the last few years, the Thermochemical Power Group (TPG) of the University of Genoa has studied the potential of a turbocharged SOFC system, considering a bio-fueled plant with nominal power output of 30 kW. Various studies have highlighted the good performance [3] and economic viability [4] of this solution. However, the integration with turbomachinery is not trivial and poses new technological challenges. In details, the system must be carefully controlled to avoid any pressure waves that could damage the ceramic electrolyte of the

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SOFC [5]. This aspect is even more critical in a turbocharged system, where the rotational speed of the compressor cannot be directly regulated, increasing the risk of surge.

For these reasons, researchers around the world have often relied on emulator plants to study the performance of SOFC hybrid systems. Integrating hardware with dynamic models in cyber-physical mode, it is possible to observe the real behavior of most of the devices, while avoiding any possible damage to the fuel cell stack, which is the most expensive and delicate component. This methodology has been successfully adopted for the emulation of SOFC-MGT hybrid systems at the German Aerospace Center (DLR) [6], at the US National Energy Technology Laboratory (NETL) [7] and by the TPG [8].

Based on these previous experiences, Ferrari et al. have designed and built the first cyber-physical emulator of a turbocharged SOFC plant [9]. This article describes the real-time dynamic model which is embedded into the turbocharged SOFC system emulator and explains how simulation software and real hardware were integrated in it. Moreover, it shows some results related to power load variations, demonstrating the proper operation of the system controllers.

2 Turbocharged SOFC system layout

The main components of the system considered for this study are an SOFC stack and a turbocharger, which are integrated as shown in Figure 1. The exhaust gases from the SOFC expand in the turbine, providing the mechanical power necessary to drive the compressor and pressurize the air flow. In this way, the operative pressure (p) of the stack increases, with a positive effect on its performance.

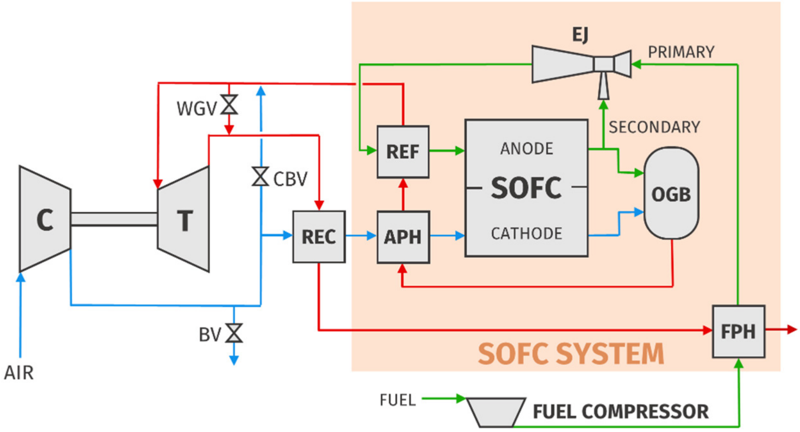

Figure 1 – Layout of the turbocharged SOFC system (air in blue, fuel in green, exhaust gases in red).

The pressurized air flow is pre-heated by passing through the recuperator (REC) and air pre-heater (APH), before entering the cathode side of the stack. The fuel (biogas with 50% CH_4 – 50% CO_2 molar composition) is compressed and warmed up in the fuel pre-heater (FPH) before entering the primary nozzle of the anode ejector (EJ). The fuel is preheated using exhaust gases from the REC. Part of the SOFC anode outlet flow is circulated back through the ejector secondary nozzle and mixed with the fuel. Then, it is used as a source of steam and heat for the reactions in the reformer (REF) that are necessary to obtain H_2 from the CH_4 in the fuel flow [10]. The anode and cathode flows are mixed at the stack outlet, and any unused fuel is burned in the off-gas burner (OGB) to provide heat for both the APH and REF. Then, the flow expands into the turbine and preheats both the air and fuel flows before being discharged into the environment. To comply with the operational constraints of the fuel cell ($\Delta T < 250$ K and $T_{max} = 1133$ K), it is possible to redirect some of the flow from downstream of the compressor to upstream of the turbine using a cold bypass valve (CBV). More details about the layout of this system and its control strategies can be found in the studies by Mantelli et al. [3,11].

3 Cyber-physical emulator plant

3.1 Experimental equipment

The real components of the test rig (Figure 2) are an automotive turbocharger, a recuperator, and a pressure vessel, which was designed to emulate the thermo-dynamic and fluid-dynamic behavior of a real SOFC stack. For this reason, the vessel contains spheres of inert ceramic material with a thermal capacitance equivalent to the one of the fuel cell. The emulator also includes two burners (CCM and CCS). The CCM is installed at the vessel inlet, and it is used to control its internal temperature (T). The CCS is installed upstream of the turbine, and it can be used to regulate the turbine inlet temperature or to start-up the system. The emulator is also equipped with a wide set of valves that can be used for control and test purposes. More details about the test rig can be found in the study by Ferrari et al. [9].

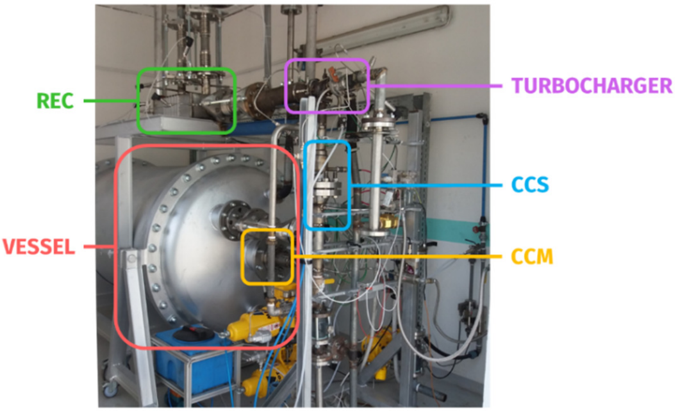

Figure 2 – The experimental equipment of the turbocharged SOFC system emulator plant.

3.2 Real-time dynamic model

A real-time dynamic model was developed in Matlab-Simulink to simulate the components that are not physically part of the experimental test rig (i.e., SOFC, APH, REF, OGB and ejector). This model is based on the library of components of TRANSEO, a dynamic modeling tool created and validated at TPG, that was previously used for the simulation of the turbocharged SOFC system [11]. Numerical schemes and iterative procedures were simplified where necessary to guarantee real-time simulation performance, which is a critical requirement to obtain a seamless cyber-physical emulation.

The SOFC is a 1D model simulating chemical and electrochemical reactions, thermal balances between the solid and the fluids, and computing the real voltage by subtracting ohmic, activation and concentration losses from the Nernst's ideal voltage. The APH is simulated by a 1D counterflow heat exchanger model. For each discretization element, the exchanged heat is determined by considering conduction through the metal plate and convection of both fluids. The REF is a 0D model which simulates CH_4 reforming and water-gas shift reactions, which are assumed to be always at equilibrium. The REF also simulates the heat exchange between air and fuel flows, which is based on the same approach of the APH model. The OGB is a 0D model simulating the combustion reaction and computing the outlet temperature from the thermal energy released by the fuel oxidation. The EJ is simulated by a 0D model that solves continuity, momentum, and energy balances to compute the recirculation ratio and the properties of the diffuser outlet flow. More information regarding these models can be found in the studies by Mantelli et al. [3,11].

The model also includes a fast Proportional Integral Derivative (PID) controller to calculate the SOFC current for obtaining the demanded power. A second PID is also used for the control of the SOFC cathode inlet temperature (constant set-point) through the air bypass valve (CBV). This second tool, based on coefficients obtained thanks the Ziegler–Nichols method, is very slow to interact in stable mode with the high thermal capacitance (slow response) of the SOFC system.

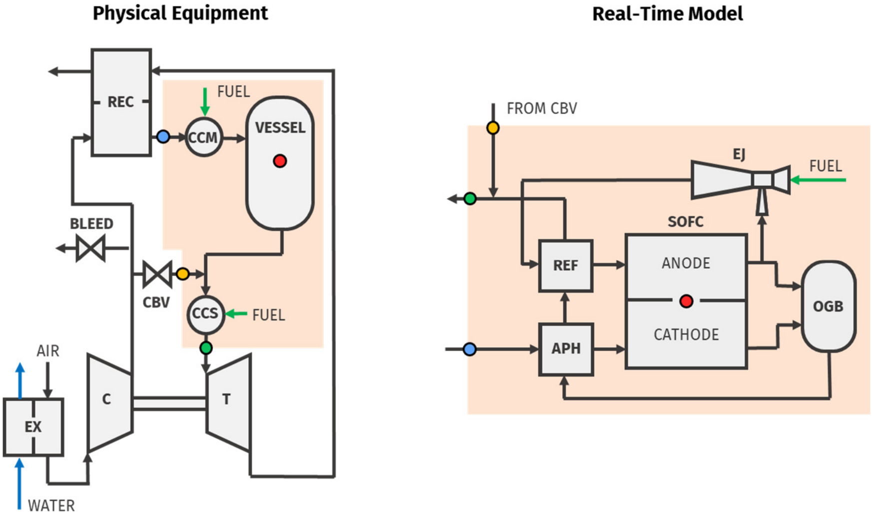

Figure 3 – Scheme of the cyber-physical integration between physical equipment (left) and model (right). The orange area represents the part of the plant that emulates the components of the model.

3.3 Cyber-physical configuration

Physical equipment and dynamic models were integrated to emulate the turbocharged SOFC system in cyber-physical configuration, according to the scheme of Figure 3. To do this, hardware and software must continuously exchange data regarding the operative state of the components and the thermophysical properties of the flows. The experimental measurements are acquired by a dedicated LabView tool through a Compact-RIO system. The LabView tool and the Matlab-Simulink model exchange information in real-time mode, via User Datagram Protocol (UDP). The dynamic model uses as inputs the thermophysical properties of the air flow at the CCM inlet (blue dot in Figure 3), and the ones of the flow bypassed through the CBV (yellow dot). Moreover, it is necessary to define within the model some additional inputs, that are not acquired from the test rig, but that are required to simulate the operation of the SOFC. They include the SOFC current and the mass flow, pressure, and chemical composition of the fuel. The consistency between simulated and real components is then guaranteed by two different controllers acting on the burners:

- The 1st one acts on the CCM to obtain a mean vessel internal temperature equal to the mean internal temperature of the SOFC computed by the model (red dot).
- The 2nd acts on the CCS to match the turbine inlet temperature computed by the model (green dot), compensating also any thermal losses between REF outlet and turbine inlet that might have been neglected by the simulation.

4 Results

Following several preliminary tests to improve the emulator in terms of safety and connection stability, a final test has been operated with the design conditions at 100% load in terms of current density (0.237 A/cm^2), voltage and Turbine Inlet Temperature (TIT), as simulated in Mantelli et al. [3,11]. In this case, the SOFC required about 44 g/s air flow and operated with 0.71 V. The power demand was managed from 100% to 80% and back again to 100% condition. However, in this test the 100% power corresponded to 24.9 kW (so the mentioned SOFC size was adapted for the integration with the emulator rig).

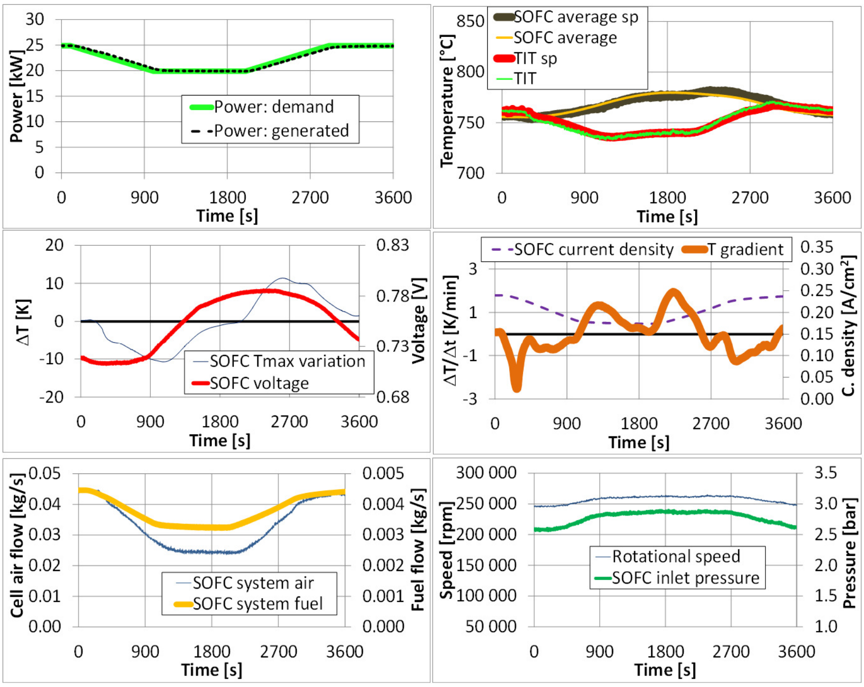

Figure 4 – Results obtained in cyber-physical mode with the design SOFC current density, voltage and TIT.

Figure 4 shows a good agreement between the calculated power and the related load demand and between the measured TIT and SOFC average temperature and the related set-point values (from the model in Matlab-Simulink). The oscillations of the SOFC maximum temperature have been maintained inside the ±12 K range and the consequent time-dependent gradient inside the ±2.6 K/min range (preventing excessive thermal stress on the component). The rotational speed trend, since the turbocharger is a free shaft, depends on the combined dynamic trends of the TIT set-point and the SOFC air mass flow rate. The fuel flow rate (the real SOFC fuel flow calculated in the model) shows a dynamic trend linked with the current density (C. density in Figure 4) one to maintain constant the fuel utilization ratio.

5 Conclusions

The results reported in this paper are essential to carry out a further step in comparison with the dynamic simulations (presented by Mantelli et al. [3,11]) on the turbocharged SOFC system. So, thanks to the emulator test rig presented in this paper, it was possible to perform an experimental validation for the proposed control system to operate this turbocharged SOFC plant. In details, the following points report the main results obtained with this work.

- The system emulation has been demonstrated effective because both TIT and SOFC average temperatures matched with good accuracy the related set-point values.
- The produced power (obtained from the model that received the inputs from the plant in real-time mode) has been in good agreement with the load demand. This is an important capability related to the system response performance.
- This test performed starting at design conditions for the current density, the voltage and the TIT has produced acceptable oscillations for both the SOFC maximum temperature (±12 K) and the related time-dependent gradient (±2.6 K/min). So, the thermal stress on the fuel cell can be considered acceptable.
- This test has successfully validated the proposed control system for the plant.

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