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Hybrid system test rig: Chemical composition emulation with steam injection

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ABSTRACT

The aim of this work is the chemical composition emulation of solid oxide fuel cell (SOFC) outlet flow, with the hybrid system emulator rig developed by TPG at the University of Genoa. To emulate this chemical composition studying its effects on a commercial machine, the layout of the test rig facility (T100 machine coupled with a modular vessel) was re-designed and expanded. This plant was equipped with a steam generator system to inject super-heated steam immediately upstream of the machine combustor. Since it is not possible to re-generate the actual SOFC outlet composition with just steam injection (fuel cell outlet flow has higher percentage value of steam and CO_2 than an expander inlet of a standard machine), this new system is essential to operate the test rig at specific chemical composition similitude condition. The objective of this new component is the developing of experimental data related to a commercial machine coupled with a fuel cell. In details, this paper deals with fuel cell outlet composition effects on main gas turbine properties because it is essential to know machine behaviour when it operates inside a hybrid system (important aspect to prevent risks such as surge).

This new layout of the facility is essential to study the effect of steam rich mass flow rate on machine behaviour. For this reason, several tests at different operative conditions were carried out with the T100 machine operating in both electrical grid-connected and stand-alone modes.

1. Introduction

The rising awareness for environmental pollution problems related to power plant emissions has increased interest in clean and high efficiency technologies. In particular, since power plant industry is the major source of greenhouse gas emissions [1], this field needs to be carefully considered to achieve Kyoto Protocol targets [2]. In this scenario, since high efficiency performance is mandatory in power generation, high temperature fuel cell hybrid systems are one of the most promising technologies for future [3]. This technology, based on the coupling of a solid oxide fuel cell (SOFC) with a gas turbine (GT), can reach a very high efficiency level (over 60% – electrical efficiency on natural gas LHV basis – as a mid-term perspective), even in small size plants, producing almost negligible emissions [4]. Furthermore, hybrid system technology produces exhaust gases at high temperature condition, useful for co-generative applications [5]. For this reason, a waste heat module can be included to utilise this thermal energy for the generation of low-grade steam, hot water, chilled water, hot air for drying or other applications [5,6].

In spite of the amount of simulation theoretical works developed in the past years [7–10] (and currently still in progress [11,12]), only one hybrid power plant, built by Siemens-Westinghouse [3], operated showing interesting performance for market penetration. In details, fuel cell hybrid systems are not ready for wide commercialisation for: their too high component costs [13] (i.e. the fuel cell) and not completely solved technological problems mainly related to the integration of fuel cell system with turbomachinery technology and to long times required for start-up and shutdown phases [14].

For this reason, the theoretical investigation activities on these innovative systems are not enough. The experimental support is mandatory to solve the problems related to machine/fuel cell coupling and to develop reliable systems for commercial distribution. However, since this fuel cell technology is expensive for test rig activities, it is possible to develop simplified emulators able to generate similar effects of a real system. These are experimental facilities designed to study various critical aspects of hybrid systems without the expensive fuel cell stacks and sometimes without turbomachines [14,15].

An important experimental study with hybrid system emulators is running at US DOE-NETL laboratories of Morgantown (WV-USA). This activity is based on a test rig designed to emulate SOFC hybrid system cathode side [16]. It includes a recuperated turbomachine, a fuel cell vessel (without ceramic material), an off-gas burner vessel, and a combustor controlled by a fuel cell real-time model [17]. Another hybrid system emulator facility is under development at German Aerospace Center (DLR), Institute of Combustion Technology, of Stuttgard (Germany) [18]. Its general

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Nomenclature

CC	Combustion Chamber
DOE	Department Of Energy
Ex	heat Exchanger
mGT	micro gas turbine
NETL	National Energy Technology Laboratory
REC	RECuperator
SOFC	Solid Oxide Fuel Cell
WHEx	Water Heat Exchanger
Variables	
c_p	constant pressure specific heat (J/kg K)
c_v	constant volume specific heat (J/kg K)
k	specific heat ratio (c_p/c_v)
LHV	low heating value (J/kg)
m	mass flow rate (kg/s)
N	rotational speed (rpm)
TIT	turbine inlet temperature (K)
TOT	turbine outlet temperature (K)
Greek symbol	
β	compressor pressure ratio

layout is similar to the NETL test rig. However, this facility includes an advanced design of the fuel cell vessel because it is able to emulate the real stack exhaust gas composition with a water cooling system (coupled with an additional combustor) [18].

At the University of Genoa (laboratory located at Savona) a complete hybrid system emulator test rig was designed and installed by TPG researchers to perform tests on both cathode and anode sides. It is currently running to study the coupling of a commercial recuperated machine with a high temperature SOFC stack. The actual fuel cell system is not present in the rig, but it is emulated by a cathodic modular vessel [19] and an anodic recirculation system. The facility was designed to emulate a hybrid system size of 450 kW (consistent with the machine size) [20]. Furthermore, the fuel cell facility was designed on the basis of the Rolls-Royce Fuel Cell Systems (RRFCS) planar stack (size: 250 kW; fuel utilisation: 75%; stack temperatures: 800–970 °C; current density: 2940 A/m^2). The anodic side emulator is composed of a compressed air line (for fuel flow emulation), an anodic single stage ejector, and an anodic vessel thermally coupled (with specially designed heat exchangers) with the cathodic side system. Furthermore, a steam generator system (boiler, pre-superheater, superheater) was designed and installed coupled with the emulator test rig. Its objective is to enhance the hybrid system emulation performance injecting superheated steam in the rig. In comparison with the DLR test rig [18], this layout is less expensive and extremely flexible to emulate the turbine inlet composition typical of a SOFC hybrid system. Since it is not possible to re-generate the actual SOFC outlet composition with just steam injection (no additional CO_2 mass flow rate is injected), the objective of this work is to operate the test rig at specific heat similitude condition. This new facility is essential to study the effect of steam rich mass flow rate on turbine behaviour showing the operational limits of the machine with different steam injected mass flow rate values.

This work tackles the hybrid system challenge related to the coupling between fuel cell and gas turbine. Before developing a prototype, it is essential to know machine behaviour when it operates inside a hybrid system (important aspect to prevent risks such as surge). In details, the paper focuses attention on the effects related to fuel cell outlet composition on the machine. For this reason, several experimental data are reported on the rig operating with the injection of a steam mass flow rate at the combustor inlet. The tests were carried out with the machine running connected to the electrical grid or in stand-alone mode.

2. Test rig layout

The hybrid system emulator test rig is composed of a commercial recuperated micro gas turbine (mGT) [21] and a fuel cell system emulator (Fig. 1). This latter facility [22] is based on a cathodic side modular vessel [22], located between recuperator outlet and combustion chamber inlet, and an anodic circuit [23].

The machine is a Turbec T100 PHS Series 3 [21] able to produce a nominal electrical power of 100 kW. Since it is a high speed micro gas turbine (nominal rotational speed: 70,000 rpm), it is equipped with a power electronic system (inverter) to produce 50 Hz conditions from the high frequency alternator current. This machine is equipped to operate in stand-alone configuration or connected to the electrical grid. The microturbine control system works at constant rotational speed when the machine is in stand-alone mode and at constant TOT in grid-connected mode [23]. This micro gas turbine consists of a complete module [21] for power generation (100 kWe at nominal conditions, N = 70,000 rpm, β = 4.45 at a TIT of 950 °C, that is 1223.15 K), a heat exchanger located downstream of the recuperator outlet (hot side) for co-generative applications, and two battery packages for the start-up phase, when the machine is in stand-alone mode.

The commercial power unit was modified for the coupling with the fuel cell emulator, as described in [22]. The original piping was substituted with four pipes for the external connections and a check valve was introduced at the compressor outlet for damage prevention due to possible surge events [22,23]. A T-joint was introduced to include a recuperator bypass line (Fig. 1).

The modular cathodic vessel was designed to emulate different fuel cell sizes and technologies. It is composed of two collector pipes [20], connected at the recuperator outlet and the combustor inlet respectively, and four module pipes connected to both collectors. These four pipes are mounted on seams for an easy volume dimension change. Both collectors and module pipes have a nominal diameter of 350 mm and their total length is around 34 m for a maximum volume of about 3.2 m^3. The maximum volume refers to a SOFC size of about 380 kW coming from a similitude approach (see [20] for details) with a RRFCS planar stack (see [20,24,25] for further SOFC details).

The anodic recirculation system, designed on the basis of a hybrid system power of about 450 kW and a system efficiency of 59% (see [20]), is composed of a compressed air line (for fuel flow emulation), an anodic single stage ejector, and an anodic vessel. The compressed air line was designed to supply the ejector primary duct with an air mass flow rate up to 20 g/s [20]. This approach was developed to emulate the fuel mass flow rate at the ejector primary duct with an air mass flow rate. The anodic ejector generates the recirculation flow rate through this system as in a typical SOFC hybrid system. The anodic volume is a nominal diameter pipe (U pipe) of 350 mm for a volume of about 0.8 m^3. As for the cathodic vessel the anodic dimension was designed on the basis of the RRFCS planar stack [20,23]. To better emulate the anodic side, it is necessary to heat up the flow in the anodic loop. For this reason a pipe based heat exchanger was developed as shown in [23] (part of the anodic loop was inserted into the cathodic volume to partially heat the anodic flow).