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Fuel flexibility for a turbocharged SOFC system

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Abstract

The aim of this paper is the analysis of a turbocharged Solid Oxide Fuel Cell (SOFC) system considering the influence of fuel composition variation. This is an innovative system layout based on the coupling of an SOFC stack with a turbocharger. The SOFC pressurization carried out with a turbocharger instead of a microturbine is a solution to combine high efficiency with reduced-cost plant layout. Moreover, the fuel flexibility is an essential issue to operate the system with different fuel compositions ranging from natural gas to biogas (considering also the CO_2 removal option).

This research activity started from the development of a steady-state system model using previously validated tools. The software was implemented in Matlab®-Simulink® environment considering the coupling of the different plant components. The analysis was started considering design conditions for a system fed by biogas (50% CH_4 and 50% CO_2 molar composition). Then, to reach fuel flexibility performance (as required for applications with renewable sources), the anodic ejector was re-designed to satisfy the related constraint for the Steam-to-Carbon ratio. The mentioned change in fuel composition involved also the control valves (bypass and/or bleed) to maintain the SOFC temperature at its set-point value, taking into account all the system constraints.

1. Introduction

Considering the critical issues [1] related to the energy generation (such as pollution, global warming and fossil fuel future termination) high efficiency systems based on renewable sources are the main perspective for future energy market [2]. One of the most interesting technologies for this scenario is related to the fuel cell based systems [3,4]. Especially the pressurized SOFC plants have significant potential perspectives for high efficiency energy production [5], including applications in the distributed generation paradigm [6-8]. In details, due to their electrochemical reactions operated at high temperature conditions (700-1000°C depending on the cell technology), these systems have different advantages, such as high efficiency (up to 60% or higher potential values in hybrid

plants), low noise, and low emissions [9]. Moreover, the application of cogeneration (heat exchangers in the exhaust duct) can guarantee a further 20% increase in the total first-principle efficiency value [10]. Another important aspect of SOFC based systems regards the possible utilization of bio-fuels (to be converted in specific reformers) [11,12]. This capability allows to operate these plants as renewable-source systems, obtaining significant benefits for the development of zero-emission technologies. So, fuel flexibility performance is an important aspect to be considered for operating with different composition biogases to almost pure methane (obtained removing the CO_2 amount) [13].

Although the mentioned positive aspects, SOFC systems (especially hybrid plants) are not ready for commercialization due to different issues, ranging from component integration problems [14] (including control system aspects not completely solved [5]) to economic issues [15]. Focusing attention on cost problems, such systems are not competitive for the following main issues: high cost of SOFC components, SOFC degradation problems and costs of the turbomachine components [16]. While different works are under development on the mentioned topics [17-19], this paper considers a turbocharger instead of a microturbine. Turbochargers can produce a significantly cost decrease [20], due to the mass manufacturing of these automotive components and the removal of electrical generator and power electronics.

The aim of this paper is the presentation of (I) the new plant layout with the turbocharged SOFC, (II) the steady-state model for both design and off-design analyses, (III) the design point of the system fed by biogas, (IV) the design point of a flexible system for fuel composition variation and (V) the related effect on the system performance. The main innovative aspects of this paper are the results related to the fuel composition change for this promising plant.

Nomenclature

APH	Air Pre-Heater	Subscripts	
FPH	Fuel Pre-Heater	AN	ANode
OGB	Off-Gas Burner	ave	average
REC	RECuperator	CAT	CAThode
REF	REFormer	in	inlet
SOFC	Solid Oxide Fuel Cell	max	maximum

Variables
P   power [W]
RR   Recirculation Ratio [-]
S/C   Steam to Carbon ratio [-] (defined as in [5])
TOT   Turbine Outlet Temperature [K]
Uf   fuel utilization factor [-] (defined as in [5])
η   efficiency [-]

2. Plant layout

This turbocharged SOFC system is based on the coupling of a fuel cell stack with a turbocharger. Therefore, this layout is able to couple the cost benefit of a mass production turbomachinery with the efficiency increase related to the SOFC pressurization (about +11% efficiency increasing the SOFC pressure from 1 bar to 5 bar [21]). If compared to a micro gas turbine hybrid system, the power is lower (10%-15%) due to the turbocharger application. Nevertheless, this design choice is motivated by the costs reduction of the turbomachine: few hundreds of euro (price for the largest turbochargers) instead of more than one thousand of euro/kW (price for microturbines) [22-24].

As shown in the system layout (Fig.1), the compressed air flow rate is pre-heated by the recuperator (recovering a part of the exhaust thermal content) and diverted to the SOFC system. Then, after a further pre-heating, the air flow duct is connected to the SOFC cathode inlet. On the fuel side (where biogases of different compositions are considered), a pre-heating is performed (using a small amount of the system exhausts) upstream of the anodic ejector. This component is necessary to generate an anodic recirculation for providing both thermal content and

steam flow for the reforming reactions. Since during all operative conditions it is necessary to avoid carbon deposition in the anodic loop, the ejector needs to be sized properly, as discussed in previous works [5,25,26]. The ejector outlet duct is connected to the reformer inlet, upstream of the SOFC anodic side. The flows discharged by the cathodic side and the anodic loop are mixed in the Off-Gas Burner (OGB) where the fuel not converted in the SOFC is burned. The OGB outlet flow is used for pre-heating the cathodic side and to supply the necessary heat to the reformer, upstream of the turbine of the turbocharger generating the power necessary for the compressor. Finally, the turbine outlet flow is used in the hot side of the recuperator and the fuel pre-heating heat exchanger.

Moreover, Fig.1 shows additional pipe lines (bleed, recirculation, bypass and wastegate) equipped with control valves. These devices are necessary to control the system, satisfying all the constraints in both design and off-design conditions (including the fuel composition change). In details, the bleed valve is used to prevent compressor surge and to control the cathode inlet temperature, while the wastegate to avoid turbocharger over-speed. Moreover, the recirculation line generates higher temperature values at the compressor inlet, and the bypass valve is able to manage the cathodic air flow (and, as a consequence, the SOFC temperature) [27].
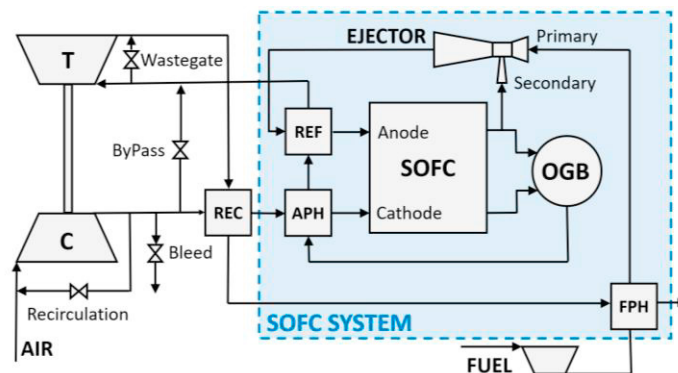

Figure 1. Plant layout.

3. Model description

The model was implemented on the basis of component tools available in Matlab®-Simulink® considering a 30 kW size system. The model of each plant component was validated against experimental data in different previous works [20,28-32]. While the reformer and SOFC tools were validated mainly in [28,31,32], the reliability verification of the other plant component models was carried out in the following works: [29] for the recuperator, [30] for the ejector and [20] for the turbocharger devices.

Global inlet-outlet balances (mass and energy equations) were considered for all the components. The OGB and the anodic ejector models are based on a 0-D approach. Instead, the SOFC, the reformer and the heat exchangers are simulated using 1-D models to correctly evaluate the not-negligible property distributions [31,32]. All the component tools were based on the following hypotheses: (I) air composed of nitrogen, oxygen, water, carbon dioxide and argon, (II) anodic flow including only the most significant species (methane, carbon monoxide, carbon dioxide, hydrogen, nitrogen and water), (III) equilibrium conditions for reforming and shifting reactions, and (IV) electrochemical reactions of carbon monoxide and methane considered negligible. The SOFC model takes into account the thermal losses of the fuel cell, while the other components external surfaces are considered adiabatic.

The SOFC model was implemented considering 10 finite elements with the calculation of Nernst's, losses and energy equations as in the following steps: (a) the consumed hydrogen is known from the current, (b) product/reactant balance is used to evaluate the chemical composition, (c) energy equation to evaluate the temperature, (d) real voltage obtained from Nernst's potential and the losses (activation, Ohmic and mass transfer). More details related to the SOFC model equations and assumptions are in [27,28].

For the other components, the following additional assumptions were considered:
- equilibrium conditions for reforming and shifting reactions (reformer);

- mass, momentum and energy global equations, necessary to calculate the recirculation on the basis of the Venturi effect [30] (ejector);
- calculation based on constant isentropic efficiency (fuel compressor);
- heat exchangers performance based on the convection and conduction heat exchange equations (REC, APH and FPH);
- interpolation of the performance maps (compressor and expander of the turbocharger);
- constant coefficient for mechanical losses (turbocharger shaft).

A further detail has to be discussed for the turbocharger model considering that standard maps were implemented because commercial turbochargers were considered not optimized for such SOFC application [20]. Moreover, these maps were scaled in agreement with the fuel cell requirements. Since it is necessary to couple the compressor with a larger turbine (not available matching considering the automotive applications), a preliminary analysis was able to show an optimal map combination for compressor and turbine. A previous work was carried out to identify a suitable turbocharger for such SOFC system [20].

4. Results

The first set of simulations has been performed setting the model as a plant designed to operate with a 50% CH_4 - 50% CO_2 (molar composition) bio-fuel and maintaining the fuel utilization factor (Uf) at 0.8 and the current density at 0.237 A/cm^2). Since fuel flexibility is an important feature of these systems, many simulations have been carried out varying the bio-fuel composition from 50% CH_4 - 50% CO_2 to a CO_2 decrease up to 100% CH_4. The results of these simulations are shown in Fig.2.
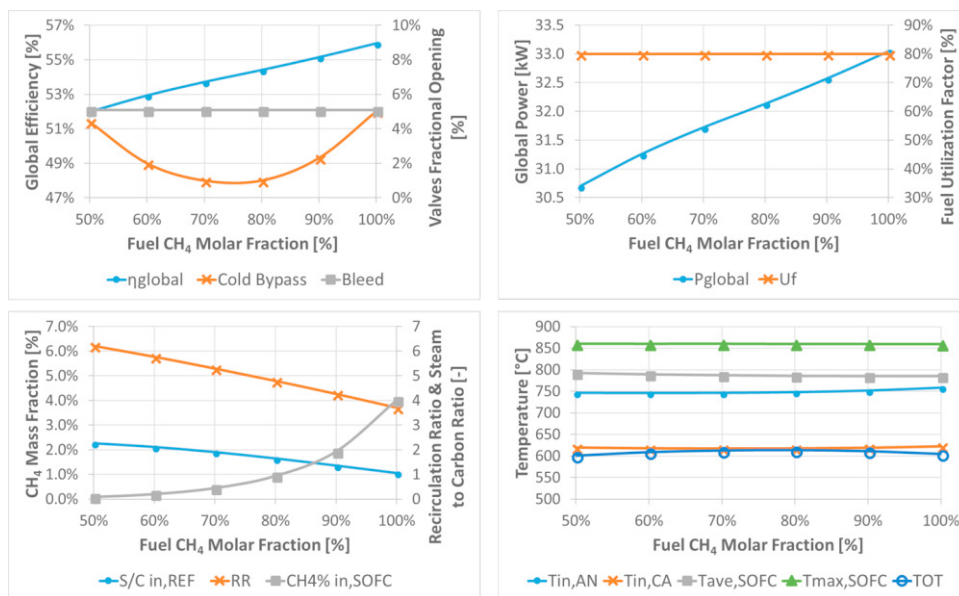

Figure 2. Performance of a turbocharged SOFC system designed to operate with a 50% CH_4 -50% CO_2 bio-fuel.

Increasing the percentage of CH_4 the global power and efficiency of the system are higher, because of the fuel higher energy content. The SOFC voltage ranges from 0.715 V to 0.758 V with the same trend of the power. The bypass and bleed valves (see Fig.1 for the location) openings have been determined in order to comply with the SOFC operational constraints (SOFC maximum temperature equal to 860°C and difference between anode and cathode temperature lower than 250°C). Since the TOT is always lower than 650°C, a standard heat exchanger can be used as REC. The main issue of this system is that, for percentages of CH_4 higher than 70%, the S/C at the reformer inlet is too low [5] (due to a too low recirculation ratio, named RR in Fig.2, that is the ratio between the secondary and the primary flows of the ejector [30]). Switching from the 50% to the 100% case in CH_4

concentration, the RR is decreasing due to the pressure decrease at the ejector inlet (necessary to obtain the required fuel mass flow rate). Moreover, the mass fraction of CH_4 at the SOFC inlet is greater with higher percentages of CH_4 in the fuel, causing a more significant fuel cell internal reforming. Thus, the anodic ejector has been re-designed to correctly operate with a 100% CH_4 fuel and a new set of simulations, whose results are shown in Fig.3, has been performed (Uf always maintained at 0.8 and the current density at 0.237 A/cm^2).

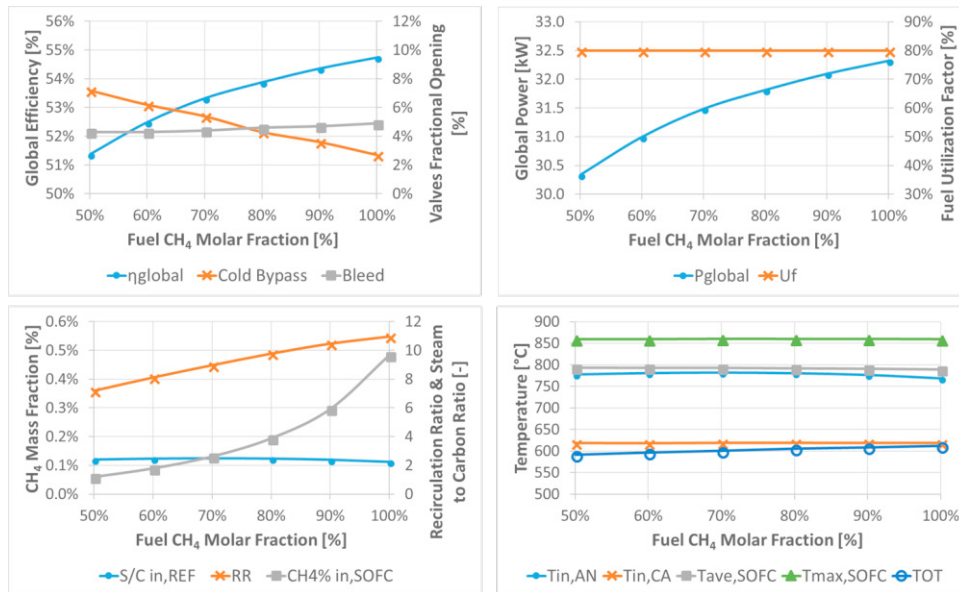

Figure 3. Performance of a turbocharged SOFC system designed to operate with a 100% CH_4 bio-fuel.

Re-designing the ejector to have a significant RR increase, the S/C is higher than 1.8 (operational limit reported in [5]) for each considered bio-fuel composition. In addition, the mass fraction of CH_4 at the SOFC inlet is much lower than its values in the previous configuration. The RR trend of Fig.3 is the opposite in comparison of what reported in Fig.2, because in this case the primary nozzle is choked, differently from the subsonic behaviour considered for the Fig.2 case (see [30] for the momentum equation responsible of the RR trend). Like in the former set of simulations, the global power and efficiency of the system increase for higher percentages of CH_4. However, their values are slightly lower. The SOFC voltage ranges from 0.713 V to 0.741 V with the same trend of the power. All the SOFC operative limits are respected thanks to the regulation of the bypass and bleed valves and the TOT is kept under 650°C.

5. Conclusions

The model of the turbocharged SOFC system developed by the Thermochemical Power Group of the University of Genoa has been used to study the plant performance varying the fuel composition. This analysis showed that, using an ejector designed to operate with a 50% CH_4 -50% CO_2 bio-fuel, the fuel flexibility of the system is limited (70% is the maximum CH_4 acceptable molar fraction). Instead, using an ejector designed to operate with a 100% CH_4 fuel, the system operative constraints are satisfied for each fuel composition in the range of 100-50% CH_4 molar fraction. The values of global power and efficiency, however, are slightly lower (2-3% decay).

Acknowledgements

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