Applied Thermal Engineering 31 (2011) 1263–1271

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Simulation model of a molten carbonate fuel cell–microturbine hybrid system

Luigi Leto [a,*], Celidonio Dispenza [a], Angelo Moreno [b], Antonio Calabrò [b]

[a] DREAM, Università di Palermo, viale delle Scienze, Ed. 9, 90128 Palermo, Italy
[b] ENEA, via Anguillarese 301, 00060 S.M. di Galeria, Roma, Italy

ARTICLE INFO

Article history:
Received 7 August 2009
Accepted 19 December 2010
Available online 5 January 2011

Keywords:
MCFC
Microturbine
Hybrid system
Simulation
Emulator

ABSTRACT

A Hybrid System based on High Temperature Fuel Cells coupled to a Microturbine allows a high efficiency, low environmental pollution and it may be exploited as a CHP System producing heat and electricity both Grid Connected and Stand Alone; the overall electrical efficiency could reach a very high value (up to 60%) and total efficiency could be over 70% including the contribution due to heat recovery.

In the context of wide research activities of ENEA on High Temperature Fuel Cells and Hybrid Systems – that involve materials, system BoP and fuels – a very great effort has been devoted to design and build, in the ENEA Research Centre of "Casaccia", an experimental Test-Rig based on a Molten Carbonate Fuel Cells Emulator and a Microturbine, to evaluate components performance characteristics at different operating conditions. To obtain relevant and reliable data and to compare them to the future experimental test results, a careful numerical simulation analysis of an Hybrid System has been developed by the Authors and it is presented in this Article. The numerical models of the System components were implemented in IPSE Pro™; the performance characteristics have been derived by evaluating operational parameters at nominal and partial loads and, moreover, a sensitivity analysis – varying main working parameters – has been performed on steady state conditions. The simulations show in detail the behaviour of both the Hybrid System and the Subsystems varying the main parameters (output electrical power, inlet flow rates, working pressure, power density, etc.) including rotational speed configuration of Microturbine.

1. Introduction

Fuel Cells are electrochemical devices suitable to direct conversion of chemical energy in electricity, with high efficiency and low pollution emissions. Among different Fuel Cells Technologies, High Temperature Fuel Cells (HTFC) operate from 600 °C to 1000 °C with more than 45% of electrical efficiency, also at partial load conditions; even when the contribution of thermal recovery is included the overall efficiency can be over 70% [1–3].

A pressurized HTFC System allows the direct coupling with a Microturbine (μGT): it is a small gas turbine (some inches of diameter) which can drive an electric generator with a rated capacity of 25–200 kW and net efficiency typically about 25–30%, rotating at very high speed (about 100,000 rpm). Microturbines are very important for a distributed production of electricity and heat because, like HTFC Systems, they may operate on site, allowing also a general reduction of electrical transmission losses [4].

By coupling a Fuel Cell System and a Microturbine we can obtain a new Energy System which presents very high electrical efficiency with a strong reduction of pollution. The performance of an HTFC–μGT System is better than a simple HTFC System or a Gas/Steam Turbine Combined System; then, the effect of the high cost of a simple HTFC system can be mitigated and a Hybrid System (HS) can be more competitive, compared to other kinds of power plants. Therefore, the coupling between Microturbines and Fuel Cells is very interesting.

The wide ENEA activity for improvement of new Hybrid Systems based on exploitation of HTFC coupled to a Microturbine includes the thorough evaluation of system performance and the optimization of plant layout through both simulation analysis and reliable experimental tests. An HTFC–μGT emulator Test-Rig (named TURBOCELL) has been designed and built in the "Casaccia" Research Centre in order to investigate on components performance characteristics at different operating conditions and with various types of fuel (mainly to evaluate microexpander performance); the Test-Rig is based on a 500 kW Molten Carbonate Fuel Cells (MCFC) emulator coupled to the Turbec T100 Microturbine and it will be ready for tests in 2011. To obtain relevant design data for TURBOCELL and to compare experimental results, a careful simulation of an Hybrid System has been developed by the Authors and presented in this Paper; the study is based on an Ansaldo Hybrid System – made up of four MCFC stacks of 125 kW assembled in an

* Corresponding author.
E-mail addresses: lleto@dream.unipa.it (L. Leto), dispenza@unipa.it (C. Dispenza), angelo.moreno@enea.it (A. Moreno), antonio.calabro@enea.it (A. Calabrò).

1359-4311/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.applthermaleng.2010.12.029

original configuration (Twinstack™) [5] – and it has been performed considering a similar subsystem based on a single MCFC stack of 125 kW [6,7].

Some models are available in open literature to study a Hybrid System; references [8–12] are useful for an indirect comparison with our results. The results of this work are reported in tables or graphics and pertain both the optimization and the evaluation of system performance. The numerical simulations show in detail the behaviour of both the Hybrid System and the Subsystems at various operating conditions (design point, sensitivity analysis by varying the main operational parameters, partial load) and they suggest some of the main characteristics of the suitable Microturbine.

2. Fuel cells–microturbine hybrid system

The Hybrid System we have considered consists of the following equipments:

- Fuel Cells Stack;
- Module of Combustion and Reforming;
- Cathodic Blower;
- Heat Exchanger, for internal heat recovery;
- Microgasturbine/Compressor Unit;
- Water–Fuel Treatment Section;
- Steam Generator for the reforming process;
- Heat Exchanger, for external heat recovery;
- Electrical Power Conditioning System.

Stack, Reforming Module and Cathodic Blower compose the Electrochemical Section (ES) which is the heart of the System. The Stack is made up of 150 Molten Carbonate Fuel Cells of 7110 cm^2 net section (8100 cm^2 gross surface) which have a rectangular geometry and work at about 650 °C and 0.35 MPa [5,8]. Air and fuel pass through the short side and the long side of the Stack and react to form carbon dioxide and steam; the chemical reactions are generated by contact of air and fuel with Ni–O-based porous cathode and Ni-based porous anode which are separated by an electrolyte consisting of molten carbonates in an inert matrix. The MCFC should feed a fuel gas containing hydrogen and carbon monoxide which acts by fuel and it allows the chemical reactions; currently a suitable fuel can be obtained using a reforming process from methane or biogas [1–3].

The Reformer and the Catalytic Burner are coupled in an original compact configuration (here named MCR) with an integrated counter-current Heat Exchanger, where the chemical reactors are together in just one equipment which has the internal separation surface as a thermal exchange wall to minimize thermal dissipation [5,8].

The methane conversion takes place with the following main typical features of both internal and external reforming:

- independence between reformer and fuel cells life;
- absence of catalyst deactivation problems;
- wide flexibility of operation;
- simple structure and maintenance;
- reduction of heat losses;
- possibility to build standard units.

The purpose of gas combustion is:

- to remove fuel in the anodic flow outgoing from the stack;
- to attain an optimum process temperature in both anodic and cathodic side;
- to allow the right operating conditions of the Stack;
- to obtain the carbon dioxide required to Stack electrochemical reactions.

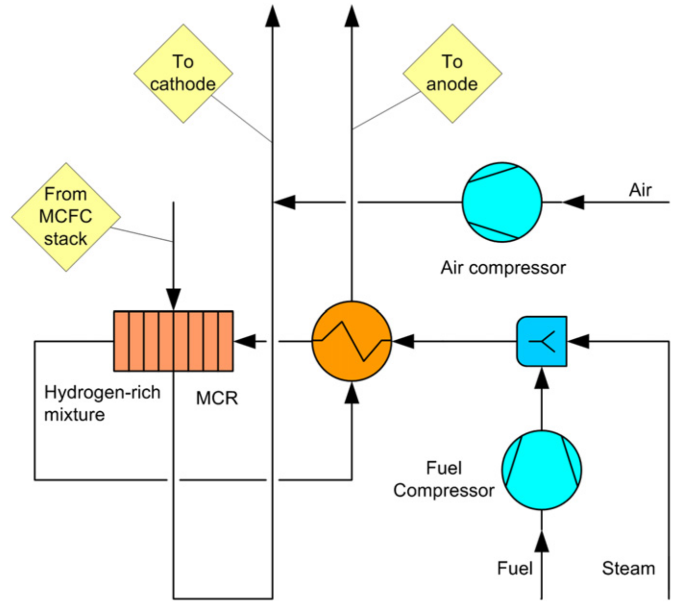

Fig. 1. Enrichment treatment of inlet gas.

At first, after a clean-up treatment, steam and natural gas are mixed and the product syngas moves to a Preheater Heat Exchanger in which a part of thermal energy of inlet anodic gas is carried away. The hydrogen-rich gas crosses the anodic side of Cells and reacts with the oxidizing gas of cathode and the electrical energy is produced by direct conversion; the exhaust anodic gas mixed with a part of cathodic exhaust gas (about 65–70% of exhaust cathodic gas is recycled) move inside the Catalytic Burner. The exhaust gas coming out from Catalytic Burner is mixed with atmospheric air before the inlet to cathode. The process flow sheet pertaining the inlet gas is shown in Fig. 1.

Downstream of the electrochemical device exhaust gas moves through a Microturbine; it produces further electricity and medium temperature heat which can be recovered and used inside the same process or in other applications. A simple block diagram is shown in Fig. 2.

3. Modelling of system components

The Hybrid System has been implemented by using IPSE Pro™ version 3.1; this software works on Windows™ platform and it is very useful for many simulations of thermochemical processes. The software includes two main subroutines – MDK and PSE – which are integrated in the code by special algorithms to minimize the computational time. In MDK (Model Development Kit) we can modify the model libraries to create new equipment, developing numerical models in MDL (Model Development Language). MDK allows the direct conversion of MDL instructions into PSE compatible code. PSE (Process Simulator Environment) is a part of the software dedicated to build a system flow sheet and to set up parameters to run simulations.

The MCFC and MCR models were not available in the equipments library. These were built in MDL language; turbomachinery, heat exchangers and other plant components have been simulated by predefined blocks. To obtain a light and suitable code, some approximations have been introduced and a one-dimensional design approach has been adopted; this method has been very useful and fast to derive the operative variables and to predict the best working conditions of single components, considering the high complexity of the system.