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Syngas feed of micro gas turbines with steam injection: Effects on performance, combustion and pollutants formation

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HIGHLIGHTS

- The performance of a MGT fed by biomass-derived syngas has been assessed.
- An algorithm based on experimental data assesses the behavior of the machines.
- An algorithm assesses the combustion kinetics of the alternative fuel.
- Steam injection is studied to assess power augmentation and emission control.

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ABSTRACT

In this work, the performance of a 100 kW Micro Gas Turbine (MGT) fed by biomass-derived Synthesis gas (S) have been assessed using a simulation algorithm, consisting of a set of equations describing the behavior of the turbomachines, the pressure losses in each component, as well as the consumption of the other auxiliary devices. An additional algorithm using Cantera's library has been developed in order to study the combustion kinetics and to assess the MGT emissions with S and with natural gas (NG) feed.

The electric power output, achieved using S with a Lower Heating Value (LHV) of about 9 MJ/kg, turns out to be similar to that achieved with NG, if a proper fuel injection strategy is adopted; efficiency is slightly lower, mainly because of the variation of the working fluid composition which involves an increase of the heat required to run the machine. In this work, the effect of the steam injection on the MGT performance characteristics has been also investigated with both NG and S. Steam injection allows to obtain higher power and efficiencies at the rated rotational speed. Attention must be paid to the risk of the compressor stall, especially when using S, as the mass flow rate processed by the compressor decreases significantly. As regards the pollutants' emission, S combustion involves a reduction of NO_X emissions of about 75%, while CO emissions slightly increase with respect to natural gas combustion. However, it was found that, with a proper fuel and steam injection strategy, the concentration of the polluting compounds can be further reduced.

Moreover, another advantage of adopting the steam injection technique lies in the increased flexibility of the system: according to the users' needs, the discharged heat can be exploited to generate steam, thus to enhance the electric performance, or to supply thermal power.

1. Introduction

Micro gas turbines (MGT) are small-scale power generation systems whose capacity ranges from 15 to 300 kWe. They consist of a compressor, a turbine, a recuperator, an alternator and an electric system, which manages the power supply to the electrical grid. Micro gas turbines design does not simply involve a scale reduction of a standard gas turbine, but a complete reassessment of the engine's architecture [1]: they operate a regenerative cycle and use radial compressor and turbine, much cheaper than axial ones and able to operate at a high rotational speed. Even if they are still an emerging technology with relatively high investment costs, MGTs offer many advantages if compared to internal combustion engines, like reduced emissions, lower weights and dimensions, easier installation, low noise and vibrations, significantly reduced maintenance, high reliability and fuel flexibility [2]. As for the efficiency, values are slightly lower in terms of electric efficiency [3] and almost similar in terms of overall cogeneration efficiency, but MGTs are still susceptible to improvement thanks to technological advancement [4].

In recent years, many studies have been focused on the possibility of

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powering MGTs with renewable fuels with low heating values, such as those obtained through processes of biomass transformation, like biogas and Syngas (S) [5–7]. Although the use of these fuels allows to further reduce the carbon footprint, additional studies are needed in order to assess the machines' behavior, the power derating as well as combustion issues in combustors designed to burn natural gas. Calabria et al. [8] carried out a numerical study of MGTs fed by several kinds of alternative fuels in order to define the critical issues encountered in the modeling of its operation. Kim et al. [9] developed a simulation tool to evaluate the performance of a commercial solution of MGT. As concerns the use of low LHV fuels, Somehsaraei et al. [10] studied a biogas-fueled 100-kWe MGT and developed and validated a model based on experimental data. A lower methane content in the fuel determines a derating of the electric efficiency and a lower amount of heat recovered by the recuperator. Liguori [11] performed a numerical analysis of the combustor of a 100-kWe MGT fueled by biogas and Natural Gas (NG) with the aim to study and limit the Nitrogen Monoxide (NO_X) emission. Using biogas instead of NG, the temperature in the final part of the primary zone increases due to the higher mass flow rate of biogas; this suggests that a better fuel control strategy and fuel distribution in the combustor should be studied; alternatively, a temperature control solution should be considered to reduce the environmental impact. As regards S, its composition is strongly dependent of the production process and it is primarily composed of Hydrogen (H_2) and Carbon Monoxide (CO) but it also has a large share of inert gases like Carbon Dioxide (CO_2) and Nitrogen (N_2). Its LHV ranges from 4 to 15 MJ/kg. As the LHV has a rather wide range of variation depending on the production technology, a specific redesign of the combustion chamber and of the fuel injection should be evaluated with particular reference to the dilution holes, to the fuel injector strategy in the pilot injector and in the main injector [12], as well as to the location of the fuel injector holes [11]. However, Delattin et al. [13] reported that the operation with syngas is possible without auto-ignition or flame stability issues if proper combustion chamber design are adopted. Other possible approaches involve the use of alternative combustion processes like the FLOX combustion [14]. In terms of power output and efficiency, the use of producer gas typically has a negative effect on the performance of MGTs and might reduce the attractiveness of this technology with respect to other CHP technologies, like Internal Combustion Engines (ICEs) [15]. The producer gas obtained by means of air gasification is characterized by a low LHV, having the nitrogen in the air a diluting effect on the gaseous products of the thermochemical conversion. This aspect makes the operation of the MGT rather complex in terms of combustion stability, amount of fuel that should be injected and risk of stall of off-design operation of the compressor and the turbine. Syngas obtained with other thermochemical conversion processes, like pyrolysis or steam gasification allows getting higher values of LHV which still require a modification of the combustion chamber, but that affect the operation of the machine to a minor extent.

A possible solution to close the performance gap with other technologies and to further limit the emissions might be the application of specific cycle modifications strategies like Humid Air Turbines (HAT), Evaporative Gas Turbines (EvGT) or the Steam-Injected Gas turbines (STIG) [16]. These solutions are traditionally used in large scale industrial and power generation turbines; depending on the adopted technology, humid cycles can be employed to enhance performance, but also to control NOx emission. A review paper by Jonsson [17] gives a comprehensive outlook of the most important works and experiences on humidified gas turbines. The basic idea of humid cycles lays in the fact that the injected water or steam downstream the compressor increases the mass flow rate in the turbine, thus increasing the specific power output. When the injected water or steam is preheated with the exhaust gas, also the cycle efficiency raises. Water or steam can also be injected directly in the combustion chamber to locally lower the combustion temperature; in this case, an additional advantage of gas turbine humid cycles is the reduction of the thermal formation of NOx in the combustion process.

Steam-injected gas turbines are widely adopted in small-scale cogeneration, in the range of few MWe [18,19], as they present a much higher flexibility of operation. A system consisting of a gas turbine and a recovery heat exchanger represents a good solution in case of constant heat demand; at reduced thermal loads, the residual heat can be used to produce steam that is injected in the gas turbine cycle to increase the electric power output.

In the micro-cogeneration scale, with electric power output ranging between 30 and 500 kWe, humidified gas cycles have only partially been studied and investigated. As MGT have compact installation and use radial machines, their behavior under humidified operation is rather different from large scale machines and some technical limitations and complexities can be encountered [20]. Steam or hot water are often generated through the recovery of the exhaust gas heat with a dedicated heat exchanger. Water is then injected downstream of the compressor or in the combustion chamber where it mixes with the compressed air [21,22]. Therefore, another advantage of humid cycles is the chance of controlling the power-to-heat ratio and to decouple power and heat generation. Power augmentation in MGTs can be also obtained with water injection upstream of the compressor [23] by cooling the inlet air in hot climates. A simulation tool developed by Stathopoulos and Paschereit [24] and based on ASPEN PLUS® was developed to simulate the Turbec T-100 MGT performance with the steam injected in the compressor outlet. Experimental tests were carried out by De Paepe et al. [25] demonstrating the positive effects of steam injection in terms of electric efficiency. Hybrid system composed of a MGT and a fuel cell were studied by Ferrari et al. [26] to assess the behavior of the turbomachine with steam injected upstream of the combustor. At a fixed electric power output, the air mass flow rate elaborated by the MGT decreases as well as the rotational speed of the machine. Running in CHP mode, the improvement in the electric performance with the STIG cycle negatively affects the thermal power that can be recovered for cogeneration purposes. Therefore, the steam injection cycle should be adopted only in presence of a reduced thermal power demand. However, with the STIG cycle, it is possible to increase the system flexibility [27]: in presence of low heat demand steam can be produced to enhance the electric performance; when, instead, high thermal power is required, the MGT can be run with the traditional cycle and increase the heat supplied to the users. Other advantages of the STIG cycle are the reduction of the capital cost of installed electric power, as well as a decrease in the NO_X formation [26].

The aim of this work is to perform a simplified analysis of the combustion process and to assess the performance and emissions of a micro gas turbine in case of methane or syngas fueling. A simulation algorithm written in Matlab, allows to evaluate the MGT's performance when fueled with natural gas or syngas, both performing a standard regenerative cycle and a regenerative cycle with steam injection in the combustor (mixed air-steam cycles, STIG). A deep insight on the variation of the operative points and criticalities of the turbomachinery when using the syngas as fuel and the STIG configuration is carried out. In addition, the power and efficiency enhancement obtained thanks to the steam injection in assessed. In order to simulate the combustion process, an additional code was written in Matlab, implementing the open source Cantera toolbox with the aim to evaluate temperature, emissions and the combustion kinetics of the MGT's combustor. This type of simulation has the advantage of being a low computational complexity algorithm, avoiding the long computational efforts required by a CFD model [28]. It also provides a sufficiently detailed description of the combustion process, giving information on the variability of operation using different fuels. Combustion was analyzed for NG and S obtained from the pyrolysis of forestry residual biomass, both in standard conditions and performing STIG cycles. Moreover, a specific management strategy for both fuel and steam injection is suggested in order to grant the performance augmentation and pollutants' formation control in the combustion chamber.