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Study of an exhaust gas recirculation equipped micro gas turbine supplied with bio-fuels

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HIGHLIGHTS

- External and internal EGR concepts applied to NOx control from micro gas turbines.
- For gaseous fuels: internal EGR is obtained by a proper location of the pilot injector.
- For liquid fuels: replacing the original radial injectors with a pressure swirl atomizer.
- We apply a CFD based method, after validation with experimental data.
- Blends of bio-fuels with fossil fuels promise noticeable benefits.

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ABSTRACT

The authors discuss in this paper some aspects related to the employment of liquid and gaseous bio-fuels in a micro-gas turbine. Besides the purpose of checking the effectiveness of methods for supplying the micro-turbine with fuels from renewable sources, the attention is focused on the need of controlling the pollutant emission. To this aim, several solutions are experienced and numerically tested. For the liquid fuel supply, a new shape and location of the main fuel injector is combined with a modified position of the pilot injector. In the case of the biogas fuelling, an external EGR option is considered as activated. Both methods aim at the reduction of the thermal and prompt NO formation by approaching the flameless combustion concept.

1. Introduction

In their recent papers [1–6], the authors have developed a comprehensive investigation of several aspects concerning the flameless concept for reduced nitric oxide emissions from micro gas turbines. The flameless combustion has been studied experimentally and/or numerically by several authors in different combustion systems [7–10] to individuate the best conditions lead to higher temperature uniformity. As well known, activating an exhaust recirculation [11–13] to the compressor inlet allows the combustion chamber to be addressed by an air-gas mixture with a relevant oxygen defect. Such a condition, together with the high temperature level induced by the recuperated cycles, leads the combustion development to situations close to the so-called MILD regime. These papers have first highlighted the advantages that arise from the adoption of an external EGR system, together a number of limitations, say:

- A performance decay that derives from the decreased compressor flow capacity and pressure ratio, because of the exhaust-air mixing.
- The increase in carbon monoxide and unburned species emissions that result from the smoother combustion regime.

In their most recent papers [4–6] the authors have demonstrated that the above problems may be partly overcome by simple, low-cost, modifications to the combustor assembly, like a different location of the pilot injector. This solution, once the optimal location has been determined, allows activation of the reactant ignition in a zone with a relevant presence of inert species, so inhibiting the thermal NOx formation.

Both solutions are of particular interest at part load operation of the micro gas turbine, because of the increased fuel flow rate that is addressed to the pilot line. In some cases, the combined employment of the modified pilot location with a limited EGR rate allows to approach emission free combustion regimes when supplying the chamber with natural gas or kerosene.

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Nomenclature

CHP	combined heat and power plant
EGR	exhaust gas recirculation
f	fuel/air ratio
LPP	lean-premixed prevaporized
$\dot{m}$	mass flow rate, [kg/s]
MGT	micro gas turbine
OFR	oxygen/fuel ratio
p	pressure, [bar]
p.p.m.	parts per million (on wet basis)
p.p.m.d.	parts per million (on dry basis)
R	reaction rate, [kmole/(m^{3}s)]
T	temperature [K]
T_{of}	standard adiabatic flame temperature [K]
X_b	recuperator by-pass ratio
X_{egr}	EGR ratio

Subscripts

a	air
ex	combustion chamber exit
f	fuel
in	combustion chamber inlet
g	exhaust gas
cc	mixing conditions
ox	oxidant
st	stoichiometric
R	recuperator

Basing on the above encouraging experiences, the authors examine in this paper the off-design conditions that are induced in the combustor by non-conventional fuels, like those pertaining to the biogases or bio-diesel category. Actually, the different fuel composition and the changes in fuel/air ratios that are needed for reaching the rated conditions of the micro-turbine can induce an off-design behaviour of the combustor and, consequently, an increase in NOx emission. In this sense the same analysis as the one carried out for conventional fuels is worthy of refinement in order to get validation from a wider range of fuelling conditions.

The numerical techniques combine a matching analysis of the whole system with a CFD simulation of the combustor and both natural gas and gaseous bio-fuels are considered. The aim is to find the optimal combination of the EGR rates and pilot injector location for minimizing the emissions in a wide range of the micro gas turbine operation.

The authors pay special attention to the challenging problem of the employment of renewable energy sources in distributed energy system: actually, a particular care must be addressed to a satisfactory compromise between the expected CO_2 reduction and possible increases in pollutant emissions, like carbon and nitric monoxides. Under this stringent aspect, examples refer to both gaseous and liquid bio-fuels. The latter case involves particular attention to be paid to the choice of the injection system, that should also ensure an effective droplet atomization and, more generally, a satisfactory mixture preparation process [6,14]. To this purpose, different low-cost solutions are examined for the shape and location of the fuel nozzles.

2. External EGR concept

Like recalled above, a number of authors' papers [1–6] provide a detailed description of the modified layout of the 110 kW micro-gas turbine, based on the introduction of an exhaust recirculation (EGR) circuit (Fig. 1). The recuperator by-pass option allows adaptation of the MGT output to different electrical and thermal power demands. This feature, together with the variable speed operation, allows a noticeable flexibility of a MGT based CHP system. If looking at constant speed operation with fully recuperated cycles, the MGT response is chiefly governed by the EGR ratio:

$$X_{egr} = \frac{\dot{m}_{egr}}{(1 - X_b)\dot{m}_g} \quad (1)$$

Increasing the above parameter allows achievement of combustion regimes close to those recognizable as *MILD* or *flameless* ones. Actually, the oxygen defect in the oxidant together with the high combustor entry temperature that results from the recuperated cycles generate conditions that allow a fair approximation of the MILD combustion regime [1,15] with much smoother temperature profiles and reduced nitric oxide formation rates.

Referring to examples that are of interest in this paper, a comprehensive overview of the EGR effects is provided by the diagrams in Figs. 2–6. The first examples regard gaseous fuels, and they are addressed to the comparison of the MGT performance and emissions with natural gas of biogas fuelling. The latter presents a typical composition (Table 1) that results from an anaerobic digestion treatment of bio-masses or organic wastes [16]. In Table 2 the expected MGT performance are reported together with a preliminary estimate of the thermal nitric oxide production at full load. Basing on these results, it could be concluded that the biogas fuelling preserves the mechanical output and efficiency levels, while it exhibits a more favourable behaviour in terms of pollutant emissions. Such indications are worthy of validation by a CFD based approach, since they result from a thermo-kinetic model [1–6] that is sensitive to overall parameters, like the adiabatic flame temperature (Table 1), the fuel and oxidant compositions and the air-fuel rates splitting into the different combustor regions.

The curves in Figs. 2–4 describe the effect of the exhaust recirculation. In particular, Fig. 2 puts into evidence that the benefits in terms of NO reduction are counterbalanced by an efficiency decrease. The latter can be explained by a decay in the thermodynamic conversion process that results from both the increased temperature level at the compressor inlet (in despite of the after cooling of the mixed species) and the decreased heat recovery effectiveness in the recuperator. The latter effect is confirmed in Fig. 3, if looking at the decrease in combustor entry temperature when the EGR ratio increases. The higher values of this temperature (by nearly 6–10 K), which can be observed for biogas fuelling, can be explained by the increased exhaust flow rate through the

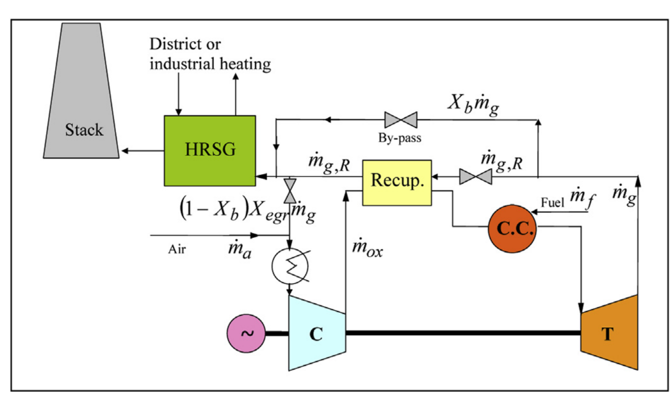

Fig. 1. Plant layout of the recuperated micro-gas turbine with the exhaust recirculation option.