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Research paper

Combustion features of a bio-fuelled micro-gas turbine

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HIGHLIGHTS

- NOx control from MGT: the methods rely on external and internal EGR concepts.
- Internal EGR obtained by a proper location of the pilot injector.
- The CFD based method was validated with experiments in a previous work.
- A flamelet based approach allows solution of complex kinetic schemes for biofuels.
- Combination of biofuels with optimized pilot location for emission control.

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ABSTRACT

The authors examine in this paper the response of a micro gas turbine (MGT) combustor when supplied with gaseous fuels from biomass treatment or solid waste pyrolysis or from an anaerobic digestion process. Actually, a sort of off-design operation is induced by the employment of low calorific value fuels both in the combustor and in the whole micro turbine system. The objective is to optimize the combustor behaviour under the point of view of combustion efficiency and pollutant control.

The first part of the paper discusses preliminary pollutant estimation, basing on a non-dimensional, time-dependent model that solves the kinetic equations for nitric oxides formation in the residence time domain. The initial conditions are derived from a thermo-fluid dynamic analysis of the MGT system under several conditions induced by the activation of a recuperator by-pass valve.

In the second part of the paper, a CFD study employs as boundary conditions those obtained from the thermo-fluid dynamic MGT simulation and it relies on different methods for approaching the fuel oxidation process. In particular, the partially stirred reactor hypothesis combined with a flamelet model is able to describe the mechanisms of both primary oxidation and pollutant formation. Several solutions are also examined in order to improve the combustion efficiency with poor calorific value fuels. The simultaneous objective of nitric oxide reduction is attained through a proper choice of an alternate location of the pilot injector aiming at exploiting a sort of internal EGR.

1. Introduction

In their papers [1–5], the authors have investigated on some topics related to micro gas turbines combustion. In particular, they have paid special attention to 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 the possible increases in pollutant emissions, like carbon and nitric monoxides. To this purpose, useful solutions can derive from the achievement of the *MILD* or flameless regime [7–11] that can be induced by either an external *EGR* [1,3] or by an appropriate choice of the pilot injector location for exploiting a sort of internal *EGR* [3,5].

The technical and scientific literature confirms that a large number of researchers have dealt with the above concepts as applied to gas turbines, in terms of both bio-fuels supply [12–19] and attempt to reach the flameless regime [7,8,10]. In Ref. [14] a CFD analysis is dealt with appropriate combustion models and detailed chemical schemes to describe the syngas combustion into micro turbine combustors.

In addition, complex and accurate combustion models have been experienced by other authors [20–32] who aimed at obtaining a detailed insight into the self-ignition and combustion

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Nomenclature

AD	Anaerobic Digestion
EGR	Exhaust Gas Recirculation
F	fuel/air ratio
$\bar{f}$	mean mixture fraction
k_b	backward reaction coefficient
k_f	forward reaction coefficient
L	combustor length
LES	Large Eddy Simulation
$\dot{m}$	mass flow rate
MGT	micro gas turbine
P	pressure
p.p.m.	parts per million
p.p.m.d.	parts per million on a dry basis
PDF	probability density function
R	reaction rate
t	time
T	temperature
T_{of}	standard adiabatic flame temperature
$\vec{v}$	velocity
x	axial coordinate
x_i	mole fraction
X_b	recuperator by-pass ratio
X_{egr}	EGR ratio
Z	atomic mass fraction

Greeks

μ	dynamic viscosity
φ	fuel/air equivalence ratio
σ_t	turbulent Prandtl number
τ	residence time

Subscripts

a	air
Ex	combustion chamber exit
f	fuel
in	combustion chamber inlet
I	referred to the primary zone
g	exhaust gas
cc	mixing conditions
ox	oxidant
st	stoichiometric
t	turbulent
R	recuperator

development, together with the identification of the pollutant formation mechanisms.

The above considerations solicited the authors to contribute to these studies with an accurate combustion analysis under the challenging off-design conditions that take place when supplying a micro gas turbine with low LHV fuels. Therefore, the numerical procedure combines a matching analysis of the whole system with a CFD simulation of the combustor. The latter is carried out with advanced techniques based on a preliminary comparison of different oxidation mechanisms and on the use of an extended kinetics scheme coupled with PDF-flamelet approach [24,26]. In Refs. [25,27] a model for the description of turbulent partially premixed combustion within RANS – CFD codes has been proposed. In particular, in Ref. [25] the authors evaluated the combustion model impact on the accuracy of results of numerical simulations of turbulent reactive flows by using two numerical codes, i.e., the Sandia Flame implementing a 3D RANS integration of the Navier–Stokes equations using the EDM, and a 1D one, where the reaction of diffusion equations are numerically integrated only along the radial direction. Others researchers have combined combustion simulation with several turbulence models [28,29]. The purpose is a reliable identification of the flammability limits as well as the flame propagation speed in reacting mixtures with low LHV fuels, under realistic conditions for a micro gas turbine combustor.

The examples in the following sections refer to a micro-gas turbine combustor fuelled with biogas from anaerobic digestion and with fuels from gasification of biomasses or solid wastes. A first estimation of the combustor response with different fuels is obtained through a thermo-kinetic model that operates within the residence time domain and predicts the thermal nitric monoxide level. After that, the authors proceed with a CFD based study. Initially, a sensitivity analysis is carried out with three different oxidation mechanisms and two turbulence models. Next, the comparison of combustion development and pollutant formation is performed by considering both natural gas and the alternate fuels. The combustion effectiveness for all these cases is widely discussed in the final part of the paper, and some solutions are proposed to improve the combustion completion and reduce the production of pollutant species.

2. The micro gas turbine operation

As stated before, the attention is focused on the main features that characterize the combustion when supplying the micro gas turbine with different fuels. A preliminary overview is then needed for examining the expected combustor response to the fuelling with either a typical natural gas or a number of gaseous fuels derived from biomass (*BIOM*) gasification or solid waste (*SW*) pyrolysis. The biomass-derived fuels may also differ in accordance with the gasification process, say oxygen (*O*) or air (*A*) based system, or anaerobic digestion (*AD*) [12]. Table 1 summarizes the chief characteristics of these fuels, in terms of composition and thermochemical properties. The fuels that have been considered present significant differences in their calorific value and in the adiabatic flame temperature as well. The first one implies that changes are

Table 1
Natural gas and biogas properties (contents of main burning species in bold).

Fuel compos. (%, molar)	Nat. gas (NG)	BIOMO	BIOMA	BIOM (AD)	SW
CH_4	**92.00**	**18.00**	**9.00**	**65.00**	**7.00**
C_2H_6	3.70	2.00	–	–	7.00
C_3H_8	1.00	2.00	–	–	7.00
C_4H_{10}	0.25	2.00	–	–	–
N_2	2.90	8.00	56.00	–	–
H_2	–	**25.00**	**9.00**	–	**18.00**
CO	–	**33.00**	**12.00**	–	**61.00**
CO_2	0.15	10.00	20.00	35.00	–
H_2O	–	–	–	–	–
Mol. mass, g/mol	17.34	21.92	28.51	25.83	23.76
LHV, kJ/kg	47,182	19,198	2798	20,183	21,697
f_{st}	0.0620	0.1680	1.257	0.145	0.1530
T_{of}, K	2220	2231	1571	2126	2300
f	0.0082	0.0214	0.191	0.0202	0.0177
φ	0.132	0.127	0.151	0.139	0.115