# Numerical analysis of biomass-derived gaseous fuels fired in a RQL micro gas turbine combustion chamber - Preliminary results.

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# NOMENCLATURE

#### Acronyms

CC	Combustion Chamber
CFD	Computational Fluid Dynamics
EBU	Eddy Break Up
NA-PPDF	Non-adiabatic PPDF
IPRP	Integrated Pyrolysis Regenerated Plant
NG	Natural Gas
Μ	Molecule
MGT	Micro Gas Turbine
PPDF	Presumed Probability Density Function
RANS	Reynolds Averaged Navier Stokes
RQL	Rich Quick Lean
SG	Synthesis Gas (Syngas)
WI	Wobbe Index

#### Parameters

AFR	air fuel ratio	kg/kg
AFT	adiabatic flame temperature	K
LHV	Lower Heating Value	kJ/kg
'n	mass flow rate	kg/s
Р	pressure	bar
Т	temperature	K
TIT	turbine inlet temperature	K
W	power	kW
${\Phi}$	equivalence ratio	

#### Subscripts

а	air
Ε	electrical
f	fuel
g	flue gas
S	stoichiometric

# ABSTRACT

The economically sustainable availability of biomass residuals and the growing need to reduce carbon dioxide emissions from power generation facilities has driven the development of a series of processes that lead to the production of a variety of biomass-derived fuels gaseous fuels, such as syngas, pyrolysis gas, landfill gas and digester gas. These technologies can find an ideal coupling when used for fuelling micro gas turbines, especially for distributed power generation applications, in a range between 50 and 500 kW<sub>E</sub>. This paper features a report on numerical activity carried out at the University of Perugia on a 80 kW<sub>E</sub> micro gas turbine annular combustion chamber, featuring RQL technology, that has been numerically modeled in order to verify combustion requirements, principally in terms of air/fuel ratio and lower heating value, simulating mixtures with varying chemical composition. The use of CFD turbulence and combustion modeling, via both Eddy Break-up and non-adiabatic PPDF methods, allows us to evaluate flame temperatures and stability, NO<sub>x</sub> and unburnt hydrocarbons emissions, under various load conditions, for the different fuel mixtures taken into account.

# INTRODUCTION

The biomass-derived gaseous fuels for energy conversion are considered to be a key element in reaching the objectives of sustainability subscribed to in the Kyoto Agreement [1], because they allow the reduction in the use of fossil fuels while at the same time obtaining a zero balance between the  $CO_2$  absorbed during the plant's life cycle and the  $CO_2$  reintroduced during conversion process of biomass and combustion. Furthermore, the use of residual biomass and wastes for conversion into gaseous fuels has the double advantage to dispose of material and have a raw material at low cost.

However, the lack of adequate energy conversion technology for small sizes limits its use to medium and large-scale plants, incurring high plant costs, logistical difficulties for the harvesting and transport of the biomass and poorly tolerated social and environmental effects.

Small or micro-scale conversion, which is certainly of lesser social impact, would make it possible to decentralize plants in rural areas where the availability of biomass is greater and would reduce transport costs. The generation of electricity in isolated communities would resolve the problems of supply and the inevitable losses in the distribution grid. Finally, distributed generation has facilitated approval procedures which can help undo the various bureaucratic knots which often obstruct the construction of new medium and large-scale plants.

# **OBJECTIVES**

The objective of this work is to assess, by CFD analysis, the performance of a MGT annular combustion chamber fueled with various gaseous fuels derived from biomass and the effect on the overall cycle performance and emissions. The results of simulations of biomass syngases combustion in a combustion chamber, modified in order to be optimized to burn low LHV gas, are compared to study the properties of the flue gas both to assess the functioning of the turbine and the emissions. Then the investigation takes into account the turbine inlet conditions in terms of temperature, pressure and mass flow rate and the pollutant emissions in the flue gas, in terms of CO, CO<sub>2</sub> and NO<sub>x</sub> concentrations. In this framework an IPRP (Integrated Pyrolysis Regenerated Plant) pilot unit was designed and built at the University of Perugia (Figure 1), based on a rotary kiln pyrolyzer, coupled to a 80 kW<sub>e</sub> micro gas turbine [2,3].



Figure 1: IPRP Pilot plant in Terni, Italy

# **BIOMASS-DERIVED GASEOUS FUELS**

A number of processes allow the transformation of biomass into gaseous fuels. Conversion from biomass to syngas can be performed through biological processes, such anaerobic digestion of biomass or waste, or thermal processes, such as gasification and pyrolysis [4]. Syngases derived from biomass through different processes (anaerobic, gasification and pyrolysis) present different fractions of chemical species (CH<sub>4</sub>, CO<sub>2</sub>, CO, H<sub>2</sub>O, O<sub>2</sub>, N<sub>2</sub>) and consequently different flame speed, ignition properties, LHV, moisture content and Wobbe index which influence the combustion process [5,6]. The syngases used as inlet fuels in the analyzed MGT combustion are a digester gas and a landfill gas, derived through anaerobic digestion, a wood gas derived through pyrolysis, and a producer gas derived through gasification. Biomass-derived gaseous fuels combustion was also compared to combustion of a syngas derived from NG through the chemical process of reforming. The compositions of these syngases were found in the Literature [4-7] and their properties are shown in table 1 with some property of the gases.

Table 1: Biomass-derived gaseous fuels used in this study

	Digester	Landfill	Wood	Producer	Reformed
	gas [7]	gas [6]	Gas [9]	Gas [5]	NG [7]
$CH_4$	60	44.0	16.2	24.6	39.7
$(\%_{\rm vol})$					
CO	-	-	53.5	15.2	0.9
$(\%_{\rm vol})$					
CO <sub>2</sub>	38	40.1	5.0	10.6	11.9
$(\%_{vol})$					
$H_2$	-	-	25.3	9.6	46.7
$(\%_{vol})$					
$O_2$	-	2.6	-	-	-
(% <sub>vol</sub> )					
$N_2$	2	13.3	-	40.0	0.8
$(\%_{\rm vol})$					
LHV	17903	12073	16883	10868	33346
[KJ/kg]					
$\alpha_{st}$	6.12	4.01	4.86	3.49	10.88
WI	22.32	15.70	18.24	12.85	28.90
MJ/Nm <sup>3</sup>					

# MGT AND CC DESCRIPTION

#### Micro Gas Turbine

The MGT is an ELLIOTT TA 80 R. It is a regenerated turbo compressor with a radial geometry and a cycle which at full load is the electrical power of the machine rated 80 kW<sub>e</sub> in operation with NG fuelling.

<u>Combustion Chamber</u> The combustor of the MGT is an annular combustion chamber with a configuration of a RQL (Rich Combustion, Quick Mix, Lean combustion).

Previous studies, consisting of numerical and experimental analysis, have been carried out to adapt this combustor to burn

low LHV gas with acceptable performance [8-9]. According to the obtained results, a CC with a modified geometry of the injectors and a smaller number of holes for the access of dilution air has been adopted because it is the most suitable for the combustion of low LHV gas, such as gas-derived biomass. The modified injectors allow, through increasing mass flow of low LHV gas, to provide the same amount of energy with respect to methane with less pressure losses. The lower dilution consents to have an appropriate value of TIT in case of low LHV gases combustion, avoiding a too low temperature at the turbine inlet [8 - 9].

Figure 2 shows the modified CC and injector for the low LHV gases.



Figure 2: Modified CC for MGT ELLIOTT TA-80 R.

RQL Combustion chambers were introduced in the early eighties as a strategy to contain emissions of  $NO_x$  in combustion systems for gas turbine in aeronautical applications. The RQL combustor technology is of growing interest in stationary applications for its effectiveness in treating fuels with complex composition biomass gaseous fuels [10-11].

With reference to Fig.2, a rich combustion in the primary zone (A) improves the stability of the combustion reaction through the production and maintaining a high concentration of hydrogen energy and hydrocarbon radical species, and secondly, it minimizes the production of nitrogen oxides due to the relatively low temperature and low oxygen intermediates between species. Effluents from the rich zone have a high concentration of hydrocarbon species, hydrogen and carbon monoxide, partially oxidized and partially pyrolyzed which require an additional supply of oxygen. This is done by injecting a large amount of air through the secondary air jets, in the Quick mix zone (B). Finally a dilution air, in the Lean-burn zone (C) lowers the temperature to avoid the spoiling of the integrity of the turbine blades. Ideally, this will lead to the emission of an effluent comprising the main combustion products (CO<sub>2</sub>, H<sub>2</sub>O, N<sub>2</sub>, O<sub>2</sub>) and an almost zero concentration of pollutants (NOx, CO) [13].

The equivalence ratio  $\Phi$  of the Elliott TA 80 R turbine, for the operation at full power, is equal to 2.0 in the rich combustion zone and 0.5 in the area of lean burn. The zones are separated by dam walls in which are placed inside the secondary air holes and the area of rapid mixing. The fuel is injected into the combustion rich zone, with 12 injectors placed inside the mixing tube. The axis of the injector is tilted compared to that of the mixing tube to allow the fuel to interfere with the inner wall of the tube and mixed with air before entering the combustion rich zone.

## METHODOLOGY

The numerical activity consists of CFD simulations of biomass derived gaseous fuels combustion in a annular CC with modified design for low LHV gas.

#### Numerical Code

The numerical simulations were carried out with the commercial CFD code STAR CCM+, a product of CD-ADAPCO [14].

Physical modeling involves, for the fluid region, an ideal gas mixture, with non-premixed Hybrid Kinetics/Eddy Break-Up combustion and PPDF equilibrium Thermal NO<sub>x</sub> models. The RANS turbulence model was switched from Standard *K*- $\varepsilon$  to Realizable *K*- $\varepsilon$ , as some numerical instability was experienced. All simulation were performed assuming steady state conditions.

#### Computational domain

For the numerical analysis, a 30 degree sector of the annular CC, which contains one mixing tube, is used, due to the periodical cylindrical symmetry of the volume.

The computational domains consist of two regions, a fluid and another solid. The solid region, corresponding to the CC, is set with the physical properties of Alloy-X (density, specific heat, thermal conductivity) [13]. In Fig. 3 the two regions of the computational domains are shown.

#### Mesh Grid

The volume grids used in numerical analysis are generated within STAR-CCM+. A polyhedral mesh model was used, leading to the following number of cells: 960,703 cells in fluid region and 278,906 cells in solid region. Through defining volume shapes, the grids are generated customizing the cell dimensions in order to have smaller cells in critical areas such as the injection zone, the mixing zone and the volume where combustion takes place.



Figure 3: Computational domain - solid and fluid regions.

# Chemical Scheme

A chemistry mechanism, involving a mixture of 7 gaseous compounds (CH<sub>4</sub>, CO, CO<sub>2</sub>, H<sub>2</sub>, H<sub>2</sub>O, O<sub>2</sub>, N<sub>2</sub>) and 9 reactions, has been implemented into an Hybrid Kinetics/Eddy Break-Up non-premixed combustion model. This scheme is based on 2 reduced mechanisms found in the Literature: the 2-step Westbrook and Dryer [15, 16] for CH<sub>4</sub> and CO oxidation and the 4-step Jones and Lindstedt mechanism [17] for the dissociation of CH<sub>4</sub> to H<sub>2</sub> for H<sub>2</sub> oxidation and reaction between CO and H<sub>2</sub>O. This chemical scheme was first presented and experimentally validated in [10].

A non-adiabatic PPDF approach was used to model Thermal  $NO_x$  formation [14].

#### **Boundary Conditions**

In order to model the combustion of the different gases taken into account, operating conditions were calculated imposing the same value of fuel thermal load and of volume-averaged equivalence ratio, as in [11] for NG firing at full load (80  $kW_e$ ).

$$W_t = \dot{m}_{fuel}(NG) * LHV(NG) = \dot{m}_{fuel}(SG) * LHV(SG)$$

$$\overline{\Phi} = \frac{\frac{\dot{m}_{fuel}(NG)}{\dot{m}_{air}(NG)}}{\left(\frac{\dot{m}_{fuel}(NG)}{\dot{m}_{air}(NG)}\right)_{st}} = \frac{\frac{\dot{m}_{fuel}(SG)}{\dot{m}_{air}(SG)}}{\left(\frac{\dot{m}_{fuel}(SG)}{\dot{m}_{air}(SG)}\right)_{st}}$$

Table 2 shows the values mass flow rate of fuel and air in inlet boundary conditions for the different biomass syngases. For the values of temperature and pressure of fuel and air in inlet boundary conditions, it was chosen to adopt the values experimentally measured in full load operation of turbine fired with NG. Values are shown in Table 3.

Table 2: Boundary Conditions – air and fuel mass flow rate

	<i>ṁ<sub>air</sub></i> [kg/s]	$\dot{m}_{fuel} \; [ m kg/s]$
Digester gas	0.0733	0.0015
Landfill gas	0.0712	0.0023
Wood gas	0.0617	0.0016
Producer gas	0.0688	0.0025
Reformed NG	0.0699	0.0008

Table 3: Boundary Conditions - temperature and pressure for fee	d air
and fuel	

	T [K]	P [bar]
Air	812	3.834
Fuel	290	5.8

#### **RESULTS AND DISCUSSION**

The comparison between computational analysis of different biomass-derived gaseous fuels combustion was carried out at full load conditions and data obtained are shown in Tables 4 and 6.

**Table 4**: Biomass-derived firing in a low-LHV gas optimized CC. Flue temperature, pressure and mass flow rate at CC outlet for full load conditions.

	$T_g[\mathbf{K}]$	$P_g$ [bar]	$\dot{m}_g$ [kg/s]
Digester gas	1107.7	3.713	0.898
Landfill gas	1121.5	3.722	0.881
Wood gas	1166.2	3.712	0.760
Producer gas	1120.0	3.730	0.856
Reformed NG	1127.3	3.724	0.849

Values of temperature of flue gas in outlet from the CC, resulting from CFD analysis, are in good agreement with the experimentally measured TIT for NG combustion [11], equal to 1126 K.

Table 5 shows the results of a MTG cycle performance analysis, in terms of generated electric power and thermal efficiency, highlighting the fact that maximum nominal power cannot be reached under low-LHV gas firing conditions.

Wood gas firing, with its high TIT, results in the best electrical power and efficiency figures.

Table 5: Cycle power and thermal efficiency

	$W_{E}[kW]$	$\eta_{el}$
Digester gas	73.62	22.84 %

Landfill gas	76.38	22.92 %
Wood gas	77.16	23.81 %
Producer gas	76.22	23.38 %
Reformed NG	72.50	22.64 %

**Table 6**: Biomass-derived firing in a low-LHV gas optimized CC. Flue gas composition at CC outlet for full load conditions.

	CO [ppmvd@15%O <sub>2</sub> ]	NO <sub>x</sub> [ppmvd@15% O <sub>2</sub> ]	O <sub>2</sub> [% vol <sub>d</sub> ]	$N_2$ [%vol <sub>d</sub> ]	CO <sub>2</sub> [% vol <sub>d</sub> ]
Digester gas	90	16	18.37	79.36	2.26
Landfill gas	220	6	18.23	79.03	2.73
Wood gas	102	92	18.73	79.97	2.90
Producer gas	170	3	18.04	79.76	2.20
Reformed NG	70	72	18.49	79.10	2.40

Figure 3 shows the temperature distribution in a transversal plane, intersecting the mixing tube and the injector, and in a longitudinal plane, intersecting the combustion chamber and the air inlet channel. For digester gas firing, the presence of high  $CH_4$  concentration leads to high temperatures, aiding CO-to-CO<sub>2</sub> oxidation mechanisms, despite the presence of CO<sub>2</sub> in the fuel mixture.

Landfill gas firing has the highest CO emissions, due to relatively low temperatures, especially in the Rich-Burn region, and to the presence of inert species, such as  $CO_2$  and  $N_2$ .

Wood gas firing, despite the abundance of CO in the fuel mixture shows the presence of a relatively low carbon monoxide concentration in flue gases; in fact, the high content of CO<sub>2</sub> at the exhaust reveals that the presence of H<sub>2</sub> effectively promotes high-temperature CO oxidation mechanisms [18], by enhancing the direct reaction of:

$$H_2 + 1/2 O_2 <=> H_2 O_2$$

via the rate exponent dependence  $[H_2]^{0.25}[O_2]^{1.5}$ . This allows to obtain a concentration of  $H_2O$ , a reagent for the reaction:

$$CO + H_2O \iff CO_2 + H_2$$

whose direct reaction rate depend upon the product of molar

# concentrations [CO][H<sub>2</sub>O].

This remains valid for the Reformed NG case as well, having an even higher volume fraction of hydrogen, leading to the lowest CO emissions experienced in this study, while producer gas, because of its composition, has intermediate values between those of the landfill gas and reformed NG.



Figure 4: Temperature distributions in longitudinal and transversal planes for all cases



Figure 5: Mass fraction of NO<sub>x</sub> on a longitudinal plane

Nitrogen oxide formation appears to be strictly correlated to peak temperatures found in the CC (Table 7), since flue gas outlet temperatures are similar for all five cases. Peak conditions are experienced in the Quick-Mix region, where quasi-stoichiometric values for equivalence ratio ( $\phi \approx 1.05$ -1.1) are reached

Figure 5 presents spatial distributions of NO mass fraction inside the combustion chamber. The RQL design allows to effectively reduce  $NO_x$  emissions by using dilution air for generating a Lean-Burn region, just before the combustion chamber outlet to the radial turbine.

Figure 6 shows temperature distributions in the solid part of numerical domain, corresponding to the CC liner. All cases produce the highest temperatures at the bottom of the Rich-Burn region; this is presumably due to a less effective flue gas recirculation in that zone, whilst in the Quick-Mix and Lean Burn regions higher gas velocity, driven by the gas turbine inlet, can improve heat transfer coefficients, therefore causing lower metal temperature. Peak values for each case are shown in Table 6. Reformed NG and wood gas firing produces an uneven distribution, showing relatively low temperatures in the dilution holes and dam wall area. This may generate an uneven strain distribution throughout the structure, leading to higher stress fields than in the other cases. Landfill gas, digester gas and producer gas firing generates lower average temperature, having a more even distribution and comparatively higher temperatures in the dam wall area.

	Peak Temperature [K]	NO <sub>x</sub>
		$[ppmvd@15\%O_2]$
Digester Gas	2338	16
Landfill Gas	2302	6
Wood Gas	2492	92
Producer Gas	2252	3
Reformed NG	2485	72

 Table 7: Correlation between peak temperatures and NO<sub>x</sub> flue gas concentrations

Table 8:	Peak	temperature	s reached	in	the	CC	liner
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	CC liner peak temperature [K]
Digester Gas	1401
Landfill Gas	1385
Wood Gas	1480
Producer Gas	1358
Reformed NG	1520



Figure 6: Temperature distributions in the CC liner

# CONCLUSIONS

A CFD numerical model for a MGT annular combustion chamber fired with various biomass derived gaseous fuels was carried out in CD-Adapco STAR-CCM+ environment. The combustor geometry was modified respect to the original design to optimize the combustion for low LHV gas. The gaseous fuels taken into account are derived from different processes of biomass conversion: anaerobic digestion, pyrolysis and gasification. Numerical results show a good agreement with experimental data of average temperature, pressure and mass flow rate in turbine inlet for NG combustion, for all syngases. From these results it possible to conclude that the turbine can properly work with tested biomass derived gaseous fuels using the combustion chamber optimized for low LHV gas. The analysis on the flue gas composition shows a higher value of NOx fraction for the wood gas and the reformed gas, in agreement with their higher values of peak temperature due to the composition of the inlet fuel richer of hydrogen respect the other gas. The results

concerning the fraction of CO shows highest values for landfill gas and gas producer. This is due to the higher presence of inert species in these fuels which, limiting the temperature inside the combustor, does not allow to obtain a complete oxidation.

Comparing the temperature values of the CC liner obtained for combustion of the different biomass derived gaseous fuels, a critical situation can be observed for wood and reformed gas. In fact for these gases a less uniform temperature distribution is observed, with peaks in the reach zone of the combustor that may cause high-temperature creep of the material.

# ACKNOWLEDGEMENTS

The project was co-funded by the Italian Ministry of Research in the framework of the National Relevance Research Programme - (PRIN  $n^{\circ}$  2008X733PJ).

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