EXPERIMENTAL SETUP FOR GAS TURBINES OPERATING ON ALTERNATIVE GAS FUELS

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The paper presents the background in ground applications with modified aviation gas turbines. There are presented alternative gas fuels suitable for these types of applications as well as the setup of a functional installation allowing the testing of aero-derivative gas turbines operating on synthetic gas fuels obtained from mixing natural gas and carbon dioxide, simulating landfill gas. The experimental results are processed and the performances of a modified turbo-shaft are estimated.

Keywords: gas turbine, aero-derivative, renewable fuels, experimentation, performances

Nomenclature

Uppercase

GN	natural gas
ΔH	enthalpy variation on turbine
LHV	lower heating value
P3	pressure in front of the turbine
ΔP	differential pressure on diaphragm
QA	air mass flow rate
QF	fuel mass flow rate
QG	burned gases mass flow rate
QG_RED	reduced burned gases mass flow rate
SP	output shaft power
T3M	temperature in front of the turbine

Lowercase

d	diameter of the diaphragm
minL	theoretical quantity of air necessary for combustion

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Greek

α	correction coefficient for fluid flow rate
ε	expansion coefficient
λ	air excess coefficient
π	mathematical constant
ρ_1	fluid density in front of the diaphragm

1. Introduction

A series of industrial applications developed the last decades have the advantage of using high technology, lightweight and reduced dimensions, characteristics provided by modified aviation propulsion systems. The power of aero-derivative gas turbines is mostly used for driving other machines, such as electric generators or compressors, instead of developing aerodynamic thrust.

Gas turbines originally designed for aircraft applications, such as turbojets or the core engine of turbofans, have been adapted to ground applications for producing mechanical energy by using the split output shaft configuration. The same manner has been applied to dual spool-split output shaft gas turbines, which are generally used in higher horsepower applications. As of 1993 approximately 25 billion kilowatts of electric power have been generated by gas turbines [1].

The production of renewable fuels, first occurring in the 1970's in the European energy agenda, knows a significant appeal lately due to the massive increase in the price of fossil fuels and legal restrictions imposed on emission level.

2. Aero-derivative gas turbines

Derivative gas turbines, based on aircraft original ones, offer a number of benefits for ground applications: replacement of typical large industrial gas turbines with smaller physical size ones, in the same horsepower output range; utilization of super alloys, achieving light weight without sacrificing strength, in components computer designed for maximum performance; flexibility and maintainability due to the modular concept [1]; large operating speed range; adaptability for remote control and automation; capability of continuous running, without inspection, until an indication of fault or performance variation occurs; capability of burning gas fuels available on-site [2].

The most successful transitions from flight to ground have been achieved by the large gas turbines producers based on some turboprops (Pratt & Whitney Aircraft Canada PT6/ST6), turbojets (Pratt & Whitney Aircraft J75/FT4, General Electric J79/LM1500, and Rolls Royce Avon) and the turbofans (General Electric CF6/LM2500, CF6/LM5000, CF6/LM6000, Rolls Royce RB211, and Pratt & Whitney JT8/FT8), with the LM2500 as the most commercially successful [1].

The RB 211-H63 Rolls-Royce gas turbine, developed from the aviation RB 211, rated at 38 MW, and even 44MW for wet low emission version, is expected to reach an open cycle efficiency of 41.5 per cent with a compression ratio of 25.1:1, will be available on market in 2013. The producer intends further development to up to 50 MW in future years [3].

In terms of local developments, I.N.C.D. Turbomotoare COMOTI [4] has obtained functional aero-derivative gas turbines in the 20 – 2,000 kW range, through valorisation of the aviation gas turbines with exhausted flight resource, such as: AI 20 GM, based on the AI 20 turboprop, used in mechanical drives for the backup compressors in the natural gas pumping stations on the main line at SC TRANSGAZ SA, and GTC 1000, based on TURMO IV C, used in a mechanical drive for two serial centrifugal compressors for the compression of the associated drill gas, in one SC OMV PETROM SA oil exploitation. Both operate on natural gas.

Other modifications have been applied to: M 701, military, simple flow turbojet, transformed in gas generator operating on natural gas for mechanical drives; GTE 2000 aero-derivative and ST 18 A aero-derivative each included into cogeneration plants with two independent lines, producing electric and thermal energy; TV2-117A turbo-shaft transformed for operation on gas fuels (natural gas, landfill gas) in order to be incorporated into cogeneration plants.

For most cases, it has been opted for minimum alterations consisting in modifying the injectors by calibrating the sections and replacing the injection nozzles.

3. Classic and alternative gas fuels for gas turbines

While offering a solution for the energy dependence on producing countries, the increase in global energy consumption requirements and aligning to European normatives which impose a minimum of 2% bio-fuels consumption, the renewable sources sustain the energetic independence along with the development of clean energy [5] reducing the environmental impact associated to conventional energy production.

The efficiency of the aero-derivative gas turbines and, subsequently those of the cogeneration groups, as well as the emissions' level are highly dependent on the type and properties of the fuels. Depending on the lower heating value (LHV), relative to natural gas (LHV = 30 ÷ 45 MJ/Nm^3), typical gas fuels can be classified as [6]: high heating value, LHV = 45 ÷ 190 MJ/Nm^3: butane, propane, refinery off-gas; medium heating value, LHV = 11.2 ÷ 30 MJ/Nm^3: weak natural gas, biogas; low heating value, LHV < 11.2 MJ/Nm^3: petrochemical gas, fuels resulted through gasification.

The operation of gas turbines on gas fuels has a series of advantages due to the properties of the fuels – thermal stability, high heating value, lack of soot and tar. But in order to maintain the pressure level and the flow rates, the fuel system must include a compression–measurement unit. A series of alternative gas fuels, such as biogas from different sources or syngas, can play an important role in the operation of the gas turbine cogeneration groups, but they must reach some requirements regarding the calorific value and the composition [7].

Natural gas is usually the preferred fuel due to its clean burning characteristics, harmless residuals and affordable price. It has the advantages of creating minimum pollution and requiring minimal maintenance of the gas turbine [2].

Researches have been conducted regarding the valorisation of the landfill gas in an aero-derivative gas turbine applicable to cogeneration groups, as well as other synthetically mixed fuels, with positive effect in emissions' reduction. Landfill gas resulted from waste deposits represents a cheap energy source, with a composition similar to the biogas resulted from anaerobic fermentation (45-60 % methane, 40-55 % carbon dioxide).

Table 1

Chemical composition of natural gas and alternative gas fuels

Fuel	CO_2 [%]	CH_4 [%]	CO [%]	H_2 [%]	H_2S [%]	O_2 [%]	N_2 [%]	C_2H_6 [%]	Src.
Natural gas	0 - 0.8	82 - 93	0.5 - 11.2					0 - 15.8	[8]
	0 - 0.1	98 - 99.9	0 - 0.7					0 - 0.8	[9]
Landfill gas	47	47	6						[8]
	40 - 45	50 - 55	0.2 - 0.5						[10]
	28 - 43	55 - 70	2						[11]
	30 - 45	30 - 55	0 - 0.5						[12]
	40	50	10						[13]

4. Experimental setup and gas turbine testing

The experimental setup at COMOTI's Gas Turbines Experimentation Complex is presented below, with its particularities developed for testing an aero-derivative turbo-shaft in order to operate on natural gas and alternative synthetic fuels: natural gas and carbon dioxide in different proportions, as synthetically obtained landfill gas.

The functional diagram presented in Fig. 1 follows the fuel system with two separate lines for the two fuel gas components, natural gas, from the national grid, and carbon, from tanks, joining in a homogenizer from which a central line provides the combustion fuel. The installation has been developed based on one patented by the authors [14].

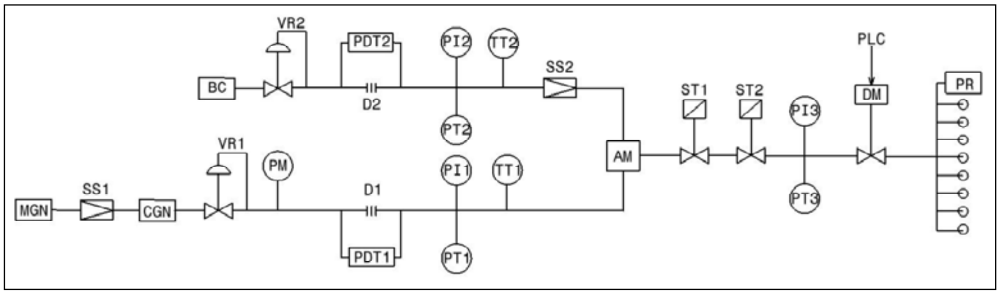

Fig. 1 Functional diagram of the gas fuel system
AM – homogenizer, BC – auxiliary fuel system, CGN – natural gas compression unit, D – diaphragm, DM – gas fuel dosimeter, MGN – natural gas grid, PDT – differential pressure transducer, PI – pressure indicator, PLC – Programmable Logic Controller, PM – pressure measurement point, PR – fuel ramp pressure measurement point, PT – pressure transducer, SS – one-way valve, ST – check valve, TT – temperature transducer, VR – pressure controller

The auxiliary fuel system is detailed in Fig. 2, containing fuel tanks from which the fuel is collected, passes through an evaporator, with the role of heating the composition during phase change in order to avoid frost at the sudden pressure drop from 120 [bar] to 3÷5 [bar], and reaches the pressure controller.

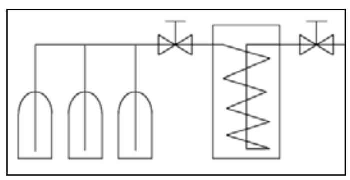

Fig. 2 Auxiliary fuel system

The natural gas line, in the lower area of Fig. 1 has, as a source, the national grid. The natural gas is compressed in the compression unit CGN, its pressure is controlled by VR1 regulator and its mass flow rate is measured using the D1 diaphragm. The auxiliary fuel line, the upper area of Fig. 1, is similar, with VR2 regulating the pressure for a good correlation of the inlet pressure of the two gases in the homogenizer, which is designed to force a uniform mixture. The PLC commands the DM which measures and controls the injected fuel mass flow rate for different operating regimes of the gas turbine. The injection ramp leads the gas fuel to the eight injectors of the gas turbine.

Table 2

Main experimental parameters

Experimental parameter	Measuring interval	Unit
P0	0 ÷ 1,5	bara
T0	-50 ÷ +150	^{0}C
PVS	0 ÷ 50	mbar
NGG *	0 ÷ 25000	rpm
NTP *	0 ÷ 15000	rpm
P2	0 ÷ 10	bara
T2	0 ÷ 800	^{0}C
T3M *	0 ÷ 1200	^{0}C
T4	0 ÷ 1000	^{0}C
T5	0 ÷ 800	^{0}C
17x2xT3 *	0 ÷ 1200	^{0}C
PGN	0 ÷ 10	bar
PAG	0 ÷ 10	bar
DPGN	0 ÷ 500	mbar
DPAG	0 ÷ 500	mbar
TGN	-15 ÷ +40	^{0}C
TAG	-15 ÷ +40	^{0}C
WF	0 ÷ 200	Nm^3/h

* Parameters requiring warning/protection

DPAG – auxiliary gas differential pressure on diaphragm, PDGN – main gas differential pressure on diaphragm, NGG – gas generator speed, NTP – power turbine speed, P0 – aspiration pressure, P2 – pressure after compressor, PAG – auxiliary gas pressure, PGN – main gas pressure, PGR – fuel pressure in the injection ramp, PVS – admission differential pressure, T0 – aspiration temperature, T2 – temperature after compressor, T3M – medium temperature in front of the turbine, T5 – temperature at exit, TAG – auxiliary gas temperature, TGN – main gas temperature, WF – fuel flow rate

The data acquisition is defined as the process of obtaining data from a different source, usually one exterior to the system. In the presented setup, it is made through electronic detection of a series of admeasurements and the processing of their results.

For data acquisition, the experimental setup includes dedicated software, with experimental sequences developed for the particular cases of interest, and last generation automatics, such as: command and control consoles with instrumentation systems for parameters’ acquisition, alarm and protection, gas detection; multi-module Programmable Logic Controller for improved data acquisition (accuracy and acquisition speed), dimensioned according to the required number and type of parameters; data acquisition system consisting in data processing equipment and pressures measurement equipment. These modular systems include the necessary elements for the acquisition and the processing of all signal types, with sampling rates of 500 kHz [4].

The tests have been developed in two stages: first operation on natural gas reaching steady operating regimes; second, after the regime stabilization, step-by-step introduction of auxiliary fuel gas, reaching the desired proportions.

5. Experimental results and performance estimation

The processing of experimental results follows few stages:

1. Data selection according to the purpose of the test (steady operation for different regimes);
2. Data correction for data collected and intermediary processed with off-grade calibrated equipments;
3. Units transformation;
4. Standard condition transformation.

The experiments have been made for the idle operating regime of the gas turbine. The large range of steady operating regimes of the gas turbine is due to the modifications from the initial helicopter gas turbine, working on kerosene, to the one working on gas fuels, consisting in eliminating the initial pneumatic aggregate elements and replacing them with a series of equipments independent form the gas turbine. Therefore, the range for which the gas turbine has been tested covers a gas generator speed of 40 ÷ 65 % of the nominal one.

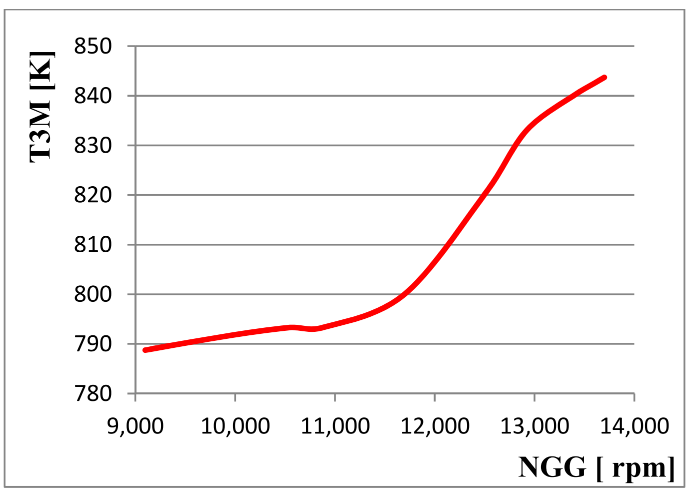

Fig. 3 Variation of medium temperature in front of the turbine depending on gas generator speed

For the first stage of the tests, the variation of the temperature in front of the turbine and the volumetric flow rate of the natural gas are presented in Fig. 3 and Fig. 4 dependent on the gas generator speed. It can be observed that the variation of the temperature for the idle operating regime varies with only 50 degrees for a 25% speed range, while, for the same range, the fuel flow rate doubles. The air mass flow rate, calculated based on experimental data, is presented in Fig. 5.

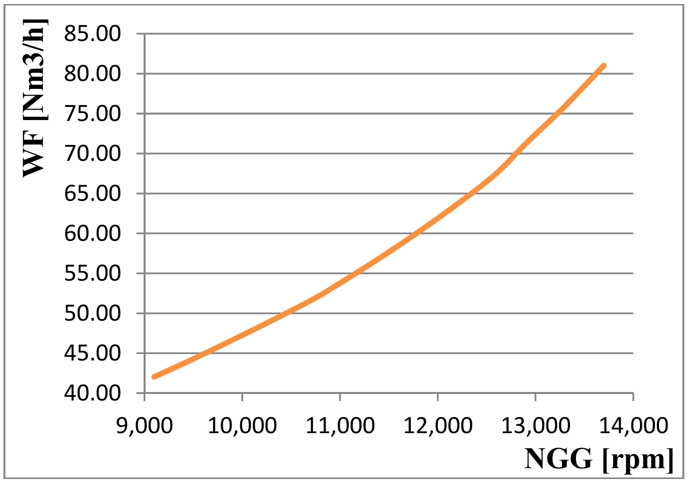

Fig. 4 Variation of natural gas flow rate depending on gas generator speed

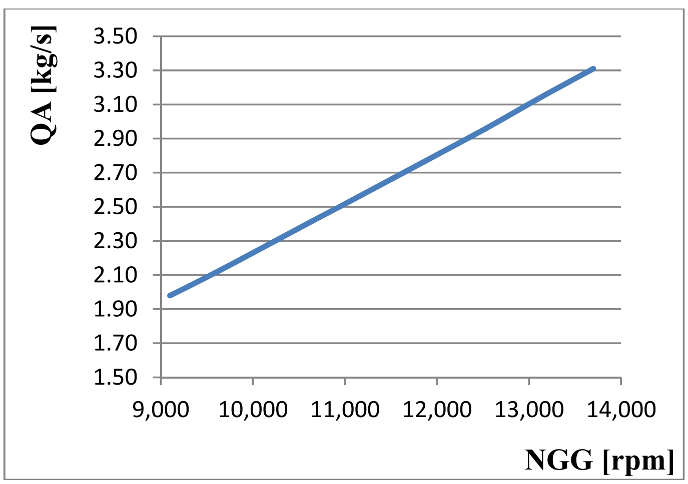

Fig. 5 Variation of air mass flow rate depending on gas generator speed

For the second stage of the tests, step-by-step introduction of auxiliary fuel gas after the operating regime stabilization, the data processing involves:

- Calculation of the fuel flow rate, due to the fact that the gas fuel dosimeter is not capable to measure the flow rate of a fluid with variable composition, being calibrated exclusively on natural gas. In order to determine the fuel flow rate, first must be calculated the flow rates of each of the two components (natural gas and carbon dioxide), Eq. (1), which requires the measurement of the parameters for each component [15]. The complexity of the installation presented in Fig. 2 is a consequence of these requirements.

$$QF = \alpha \cdot \varepsilon \cdot \frac{\pi \cdot d^2}{4} \cdot \sqrt{2 \cdot \Delta P \cdot \rho_1} \quad (1)$$

- Calculation of the fuel composition and the combustion parameters – air excess coefficient and theoretical quantity of air necessary for combustion, using experimentally determined air mass flow rate. The air excess coefficient values used for calculation have been previously determined in [16].

$$\min L = \frac{QA}{\lambda \cdot QF} \quad (2)$$

- Calculation of turbine performances for different fuel compositions, knowing the variation of the temperature on the turbine and using the approximation functions [17] for determining the enthalpy variation on the turbine. The shaft power is approximated at equal to the gas generator power.

$$SP = \frac{\Delta H \cdot QG}{2} \quad (3)$$

$$QG = QF + QA \quad (4)$$

$$QG\_RED = \frac{QG \cdot \sqrt{T3M}}{P3} \quad (5)$$

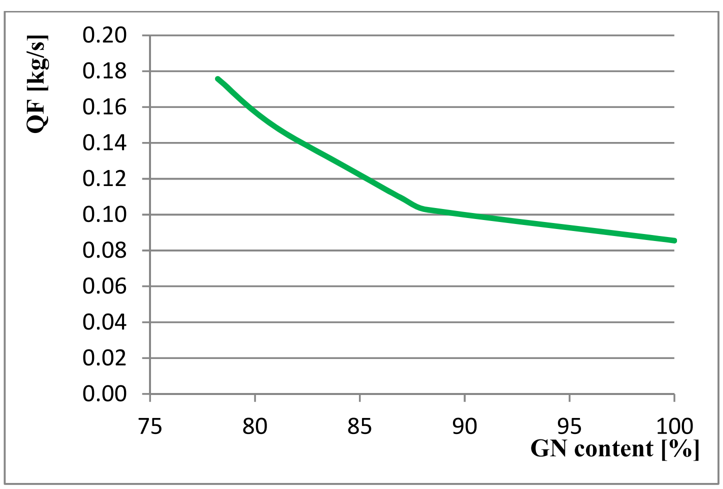

Fig. 6 Variation of synthetic fuel mass flow rate depending on its composition (idle regime)

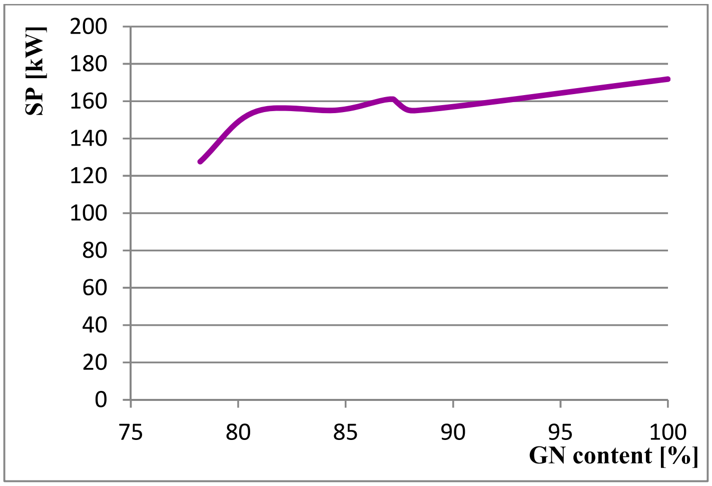

Fig. 7 Variation of power depending on fuel composition (idle regime)

In order to estimate the performances of the gas turbine for the nominal operating regime, a series of data for the operation and kerosene has been provided by the gas turbine producer [18] – air mass flow rate, fuel mass flow rate, fluid parapeters in front of the turbine, etc., therefore allowing to calculate, with the help of [19], the combustion parameters for the different fuel compositions, the fuel flow rate for each one and the shaft power developed by the power turbine. The performances are presented below, in Table 3.

It can be observed that the performances of the gas turbine are slightly lower for its operation on natural gas and increasing with the decrease of natural gas proportion in the mixture fuel. This fact can be explained by the increase in fuel flow rate, proportional with the carbon dioxide content. The performances for kerosene operation are equalled at a natural gas content of approximately 91.1 %.

Table 3

Performances for different fuels

Fuel	λ	minL	QG_RED	SP [kW]
Mixture 78 % GN	4.45	8.44	$6.4364 \cdot 10^{-3}$	1,543
Mixture 81 % GN	4.45	9.86	$6.4123 \cdot 10^{-3}$	1,537
Mixture 85 % GN	4.45	11.90	$6.3878 \cdot 10^{-3}$	1,531
Mixture 87 % GN	4.45	13.74	$6.3720 \cdot 10^{-3}$	1,527
Mixture 89 % GN	4.45	14.43	$6.3671 \cdot 10^{-3}$	1,525
100% GN	4.5	17.16	$6.3506 \cdot 10^{-3}$	1,520
Kerosene	4.6	14.6	$6.3628 \cdot 10^{-3}$	1,523

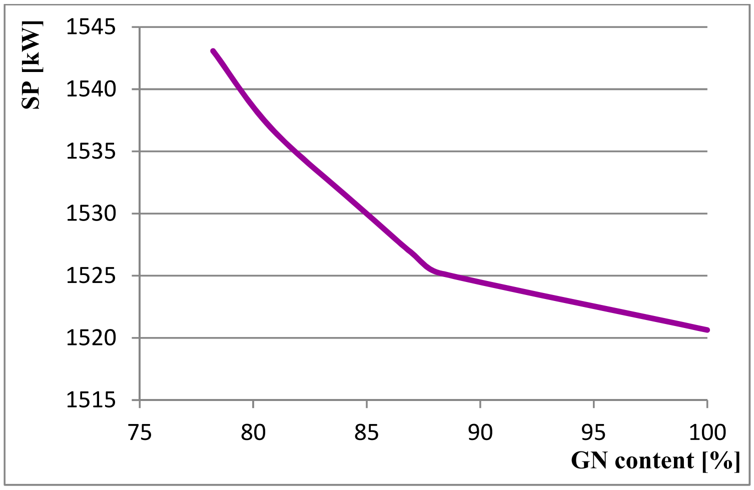

Fig. 8 Variation of power depending on fuel composition (nominal regime)

6. Conclusions

The paper presents the international and national development in aviation gas turbines modification in order to use the available high technology for ground applications. Several suitable alternative gas fuels are presented, focusing on natural gas and mixtures of natural gas and carbon dioxide, in different proportions, as landfill gas. The functional diagram of an existing installation is briefly described in order to acknowledge the method of obtaining the above mentioned mixture of gases on which an aero-derivative turbo-shaft has been tested. The last part of the paper focuses on the experimental results processing in order to estimate the performances of the gas turbine on lower operating regimes, as well as to estimate its performances on nominal operating regime.

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