Global Journal of Researches in Engineering: A
Mechanical and Mechanics Engineering
Volume 22 Issue 1 Version 1.0 Year 2022
Type: Double Blind Peer Reviewed International Research Journal
Publisher: Global Journals
Online ISSN: 2249-4596 & Print ISSN: 0975-5861

Performance of a Capstone Gas Turbine based Power Plant Working on High Butane LPG

By Carlos Romero, Yamid Carranza & Ricardo Acosta
Universidad Tecnológica de Pereira

Abstract- In this paper there are presented the results of the operational performance of a 30 kW microturbine generator (MTGs) fed with high butane content liquefied petroleum gas, while subjected to a stand-alone test procedure involving steady and transient load conditions. Neither modifications, nor regulations were made to the micro-turbine system for operation on the liquefied petroleum gas. To evaluate the performance, measurements of turbine and generator parameters were gathered from its original unit controller, as load changes were applied by changing load-bank values. For the stand-alone mode detailed graphs of the test results are presented, showing the transparency and robustness of the turbine-generator set to the used fuel, judging by the quality of the output electric parameters. The results from this performance testing provide good insight into the use of high-butane content liquefied petroleum gas as fuel for the tested microturbine. The continuous use of a fuel would need more tests to establish that the life of the critical components of the microturbine are not hampered from what they are on the baseline fuel.

Keywords: gas turbine, high butane LPG, electrical generator, performance, power generation.

GJRE-A Classification: FOR Code: 091399p

Performance of a Capstone Gas Turbine based Power Plant Working on High Butane LPG

Carlos Romero [α], Yamid Carranza [σ] & Ricardo Acosta [ρ]

Abstract- **In this paper there are presented the results of the operational performance of a 30 kW microturbine generator (MTGs) fed with high butane content liquefied petroleum gas, while subjected to a stand-alone test procedure involving steady and transient load conditions. Neither modifications, nor regulations were made to the micro-turbine system for operation on the liquefied petroleum gas. To evaluate the performance, measurements of turbine and generator parameters were gathered from its original unit controller, as load changes were applied by changing load-bank values. For the stand-alone mode detailed graphs of the test results are presented, showing the transparency and robustness of the turbine-generator set to the used fuel, judging by the quality of the output electric parameters. The results from this performance testing provide good insight into the use of high-butane content liquefied petroleum gas as fuel for the tested microturbine. The continuous use of a fuel would need more tests to establish that the life of the critical components of the microturbine are not hampered from what they are on the baseline fuel.**

The course of selected performance parameters in the microturbine generator fuelled with LPG is described in this document. The analysis of test results of the microturbine under steady-state and transient operation have been made. Both in steady state and transient conditions, values of output power, speed fluctuation, emissions, noise levels, and exhaust gas temperatures remained under acceptable levels.

Keywords: gas turbine, high butane LPG, electrical generator, performance, power generation.

I. Introducción

The need to respond in a safe, efficient and environmentally sustainable manner to the growing energy needs in the different sectors of the national economy, demands the rationalization, technical improvement and expansion of the sources of electricity supply. Responding to this demand, the Colombian Ministry of Mines and Energy, the Unit for the Mining-Energetic Planning (UPME), and the Energy and Gas Regulation Commission (CREG) lead a comprehensive policy that promotes, generates and stimulates programs and projects for the generation, saving and efficient use of energy and particularly for self-generation [1] [2] [4- 9].

The Colombian Government issued Decree 2143 of 2015 [9], through which tax incentives are regulated for the promotion, development and efficient use of energy. The micro-grids find their way, with sources of distributed generation, local storage, controlled loads, and the possibility of developing electrical islands. Colombia is promoting programs for distributed generation (DG) and will probably encourage more projects for self-generation in the commercial, residential and service sectors, emulating initiatives as that of the US Department of Energy, which promoted the Advanced Alternative Engine Systems program (ARES), designed to develop small micro-generators units of high efficiency [12]. If incentives are created for self-generation in commercial, residential and service sectors, the incorporation into the system of micro-generation units could be attractive, and the introduction of microturbine generators could be favored.

On the other hand, Colombia is currently exporting LPG, a part of which is obtained as a byproduct of natural gas purification in known fields as Cusiana. Some energy suppliers have had interest in exploring the performance behavior of power generators when they are run on high butane liquefied petroleum gas for electricity generation in oil fields. Considering the fact that to date, to the authors' knowledge, there has not been reported any experimental tests related to the performance of microturbine generator (MTG) sets fuelled with LPG from Cusiana, a 30 kW Capstone MTG fed with Cusiana LPG was tested, as a pilot experience, to judge about its power output, step response, power quality, and fuel consumption.

Microturbines are lightweight and compact in size combustion turbines with outputs of 30 kW to 400 kW that can be used for stationary energy generation applications at sites with space limitations for power production. They can be run on natural gas, biogas, propane, butane, diesel, and kerosene. Particularly, the Capstone MTG consists of a compressor, recuperator, combustor, turbine and permanent magnet generator; the air drawn through the inlet system refrigerates the generator, discarding the need of a liquid cooling system. Intake air is compressed and injected into the recuperator, a heat exchanger where it is heated by turbine exhaust. Fuel enters the system through an injection port and is mixed with the heated compressed air. The ignition system causes the air-fuel mixture to burn in the combustion chamber under constant pressure conditions; the resulting gases are allowed to expand through the turbine section to perform work, rotating the turbine blades to turn a generator, which produces electricity. The rotating components, which

---

Author α σ ρ: Universidad Tecnológica de Pereira.
e-mail: cromero@utp.edu.co

can reach 96,000 min^{-1}, are mounted on a single shaft supported by low-maintenance air bearings.

The MTG has been tested in stand-alone mode, as a power source that meets the current consumption demanded by the coupled load.

The general goals of the load test were:

- To get onsite experimental information related to the performance of the Capstone microturbine when fueled with Cusiana LPG.
- To measure the electric generation performance of the MTG under a load cycle, for the given open ambient conditions, with the available instrumentation, and the time allowed to perform the test, adjusting as far as possible to the rules of operation and tests of the MTG.
- To provide an appropriate stable medium for the reliable evaluation of electrical efficiency, and MTG performance.

The work here presented refers to the evaluation study, and is organized as follows: first, the properties of the LPG used are related, and a brief description of the Capstone micro-turbine is given. After that, this paper describes the experimental procedure and constraints. Next, the test program is described, followed by a summary of the results. Finally, the main conclusions of the work are presented.

II. MATERIALS AND METHODS

a) *Particularities of the LPG from Cusiana*

The term LPG applies widely to any mixture of propane and butane, the two constituents occurring naturally in oil and gas reservoirs that are gaseous at normal atmospheric conditions but can be liquefied by pressure alone. Components heavier than butane are liquids at normal conditions and components lighter than propane cannot be liquefied without refrigeration. The presence of butane, pentane, and heptane at concentrations of up to 40% characterize this particular LPG from Cusiana, which analysis is presented in table 1.

Table 1: Composition and physical properties of Cusiana LPG (*)

Compositional Analysis of GLP to C12+			
SamplingLocation		ALSABANA	
CylinderNumber		CLM009	
SamplingConditions		30,0 psig @ 66.0°F	
Component		Mole %	Weight %
CO2	CarbonDioxide	0,01	0,01
N2	Nitrogen	0,10	0,06
C1	Methane	0,01	0,00
C2	Ethane	3,36	2,14
C3	Propane	71,45	66,84
iC4	i-Butane	13,13	16,20
nC4	n-Butane	11,91	14,70
iC5	i-Pentane	0,03	0,05
______		______	
Totals :		100,00	100,00
Note: 0,00 meanslessthan 0,005.			
Calculated Whole Gas Properties			
Gas Gravity	1,6272	(Air = 1 @ 14,73 psia& 60°F)	
WholeSample Mole Weight	47,13	g mol^{-1}	
Ideal Gas Density	1,9831	kg m^{-3} @ 14,65 psia, 60°F	
Ideal GrossCalorificValue	2665,7	BTU·ft^{-3} @ 14,65 psia, 60°F	
Ideal Net CalorificValue	2454,5	BTU·ft^{-3} @ 14,65 psia, 60°F	
PseudoCriticalPress.	598,7	psia	
PseudoCriticalTemp.	682,1	Rankine	
Gas Compressibility Factor, Z	0,979184	@ 14,65 psia& 60°F	
GPM (C2+)	28,49		
GPM (C3+)	27,60		
Additional Information			
Real GrossCalorificValue	2722,4	BTU·ft^{-3} @ 14,65psia, 60°F	
Real Net CalorificValue	2506,6	BTU·ft^{-3} @ 14,65psia, 60°F	

* *Results of the Chromatographic test performed by Equion.*

b) Capstone micro-turbine

Microturbines have advantages over modern internal combustion engines, such as their high-power density, less moving parts and comparatively low emissions. They can be fuelled by liquid and gaseous fuels - fossil or renewable. Microturbine capacities are generally between 30 to 350 kW. The Capstone 330 MTG, made available by the company Supernova Energy Services, installed in Alsabana was subjected to service setting works, as it was new. Photographs in figure 1 allow to illustrate the general view of the MTG located at the test site.

Figure 1: Location of the MTG at the Alsabana Campus test site

The Model 330 MTG is a compact low emission solid-state controlled power generator, based on a 30 kW Capstone micro-turbine. The latter is designed for 30 kW output, uses power electronics to convert the high-frequency output of the generator to three-phase 480 volts voltages, at 50-60 Hz current frequency. The high-frequency AC current of the generator is converted to the 50-60 Hz AC current, after being processed through an inverter and a DC converter. Table 2 lists the rated capabilities of each microturbine based on available literature.

Table 2: Technical performance data of the Capstone 330 microturbine for different fuels [7]*

Fuel type	GNC (55 psig)	GLP (55 psig)	Diesel (5 psig)
Mean time to repair	20,000 h	20,000 h	20,000 h
Nominal full power	30 kW net (+/- 1 kW)	30 kW net (+/- 1 kW)	29 kW net (+/- 1 kW)
Peak efficiency (LHV**)	27% (+/- 2%)	27% (+/- 2%)	26% (+/- 2%)
Fuel consumption***	18,7 lb/h, 8,5 kg/h	19,0 lb/h, 8,6 kg/h	21,9 lb/h, 10,0 kg/h
Methane based fuel flow (Metan-HHV)	440,000 kJ/h (420,000 Btu/h)		
Methane based energy of exhaust gases	305,000 kJ/h (290,000 Btu/hr)		
Exhaust gases temperature	500°F, 261°C	500°F, 261°C	500°F, 261°C
Output voltage	250-700 VDC	250-700 VDC	250-700 VDC

* *Source: Capstone Turbine Corporation*

Since Capstone Microturbines use lean premix combustion system to achieve low emissions levels at a full power range, they require operating at high air-fuel ratio; injectors control the air-fuel ratio. The MTG is instrumented to record operational parameters (of which, temperatures, pressures, fuel usage, turbine speed, internal voltages/currents, and status are of importance for the undertaken study). The average readings of two thermocouples indicates the Turbine Exit Temperature (TET); a compressor inlet thermistor is installed to measure the air temperature at the inlet of the compressor wheel; the air flow, Wair, (in pounds per hour) and the amount of energy needed in the combustion chamber required to regulate fuel flow in the combustion chamber, W_{energy} (in Btu/sec), are calculated based on engine speed. Such data are available with a computer or modem connected to an RS-232 port on the microturbine. A schematic drawing of the built-in instrumentation supported by the microturbine generator is presented in figure 2.

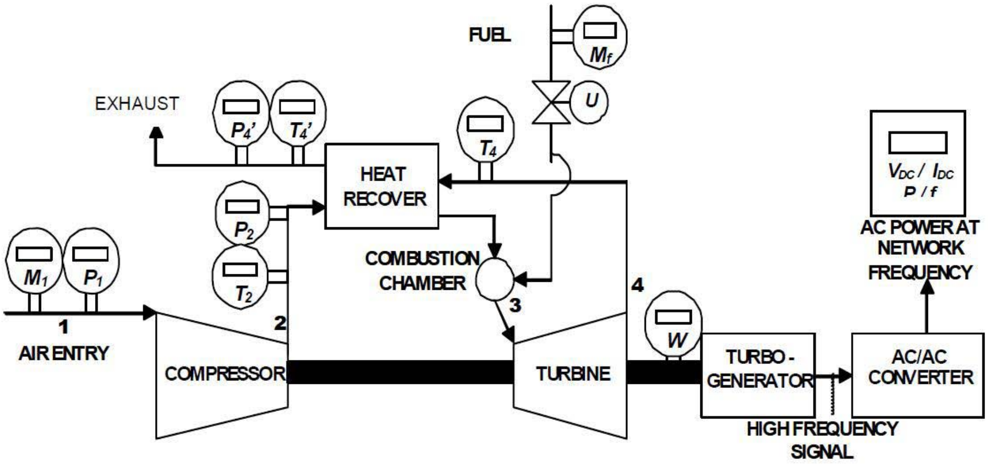

Figure 2: Schematic diagram of the instrumented power unit [3]

A large on-board battery pack is used to start the microturbine, and also to store energy when the microturbine decelerates to produce less power. To meet output power requirements automatically, the system can be configured in Auto Load mode. Auto Load ensures that the microturbine closes the output contactor to immediately produce the required output power once minimum engine load speed is reached. The output speed-power characteristic of the microturbine generator is reproduced in figure 3.

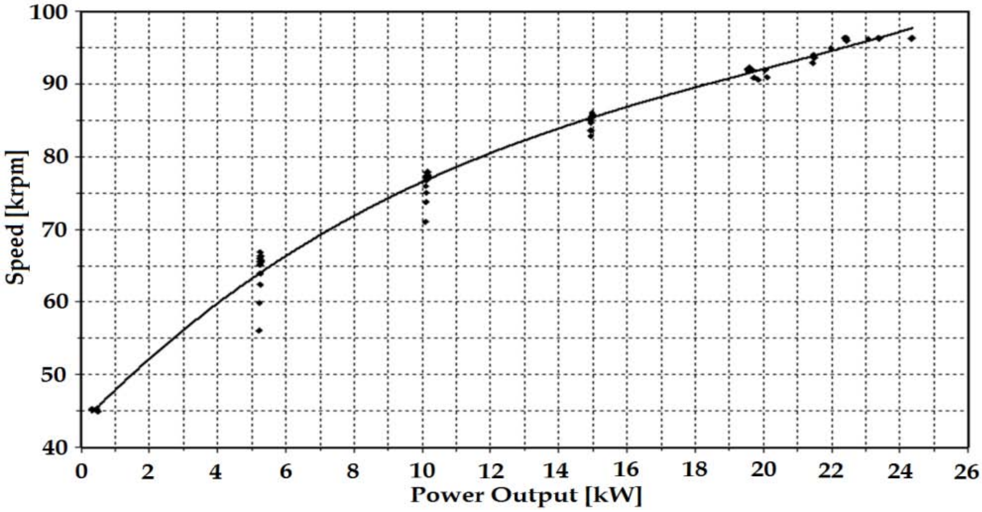

Figure 3: Microturbine speed at partial loads [3]

c) *Experimental facility and procedures*

LPG was supplied from an oil field to the test site by a tanker with a storage pressure ranged between 50 and 90 psia during the test; an intermediary damper tank was used to reduce pressure fluctuations due to consumption, and a bypass was used in the LPG supply line with its respective regulating valves before the entry of gaseous fuel to guarantee the pressure, as can be observed in the photographs of figure 4. The average ambient conditions at the time of the test were: temperature close to 14°C, 80,2% relative humidity, and 0,726 atmospheric pressure.

Figure 4: Tanker, lung tank and LPG supply bypass

The microturbine generator was connected to an Avtron 1000 kW capacity electrical resistance load bank, with a manual load setting; electric generation quality was measured with a FLUKE 434/PWR energy meter connected to the generator power output through clamp-on current transformers. This is a three-phase electrical power quality analyzer FLUKE 434/PWR with a measurement range Vrms (AC+DC) between 1-1000 V, and frequency range of 40-70 Hz. A schematic of the general layout of the test facility is shown in the figure 5.

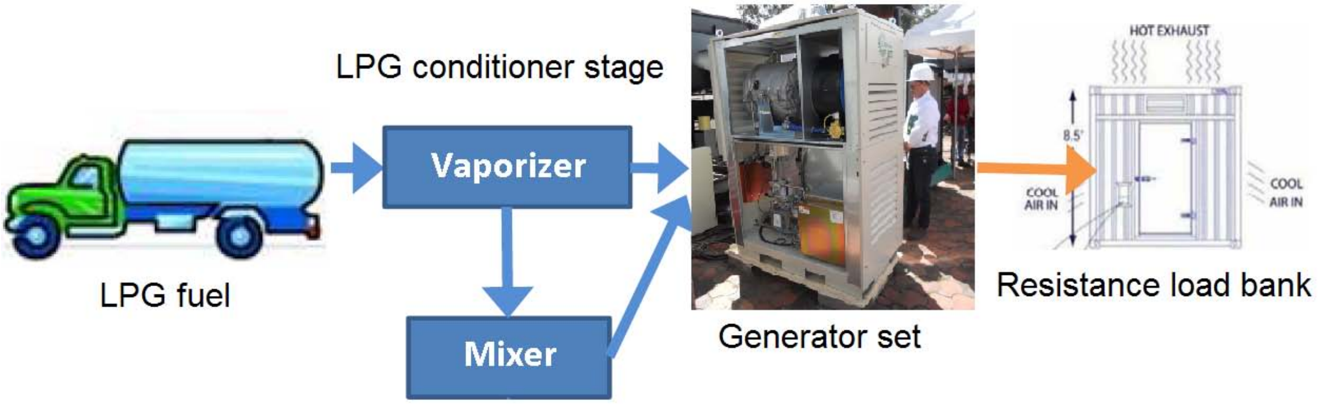

Figure 5: General layout of the test place

The procedure followed to assess electrical, thermal, and operational performance of the micro-turbine generator, comprised pretest activities, startup, idle, and a two-step load test during a short period of time. The software for the microturbine unit was configured for standalone operation through the local display panel; the turbine was started, controlled and monitored by a computer using Capstone's software.

The load test applied by the load bank, as it is shown in figure 6, consisted of a transient from idling to a 20-kW load at maximum speed of 96000 min^{-1}, a steady-state operation in this operation point for about eight minutes, followed by a drop to 3 kW power at 60000 min^{-1}, and a steady running at this load for about four minutes. In the last part of the test, the load was completed released and the microturbine was sustained idling at a speed of 45000 min^{-1}, as it is shown in figure 6. During the test, all available parameters were monitored and recorded from the MTG system. All electrical parameters (both single-phase and three-phase) were recorded at the load bank by the energy meter.

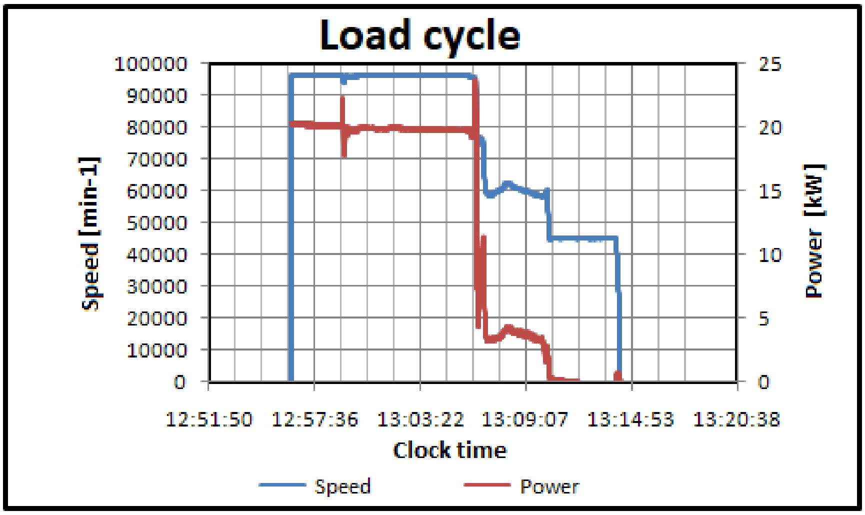

Figure 6: Load cycle followed for the MTG testing

III. Results during the Test Program

The study focused on the overall performance parameters related to engine operation. In the following, the results of the collected data during the operation cycle, and the response of the turbine-generator to load changes are presented. Initially, the results obtained from the proprietary MTG controller are presented: inlet to compressor and turbine exhaust gas temperatures, air flow, intake air temperature and pressure values. Once the behavior variables are described, the evolution graphs of the electrical power, voltage, and current delivered by the MTG are illustrated. The information thus presented allows to evaluate the behavior of the MTG operating with LPG, from the perspective of stable operating capacity and within the mechanical, thermal, environmental limits.

a) *Mean-variable measurement results*

The microturbine generator has presented a normal behavior during the test, judging by the values of the speed, power, inlet to the turbine and compressor temperatures, load percentage, among the operating parameters registered by the proprietary controller of the microturbine; a summary of those performance parameters is presented in table 3.

Table 7: MTG operating parameters registered during the test period

Tiempo [min:s]	Speed [min^{-1}]	Power [W]	TET [F]	TEC [F]	Wair [pph]	Amb. pressure [psia]	Suplied energy W_{energy} (btu/s)	Accel. [%]	Frequency [Hz]
00:0	96320	20277	1102,2	69,9	1694	10,7	46,6	60,8	60
00:01	96236	20369	1101,2	69,9	1695	10,7	47,2	60,3	60
02:49	94028	18104	1109,8	72	1614	10,6	41	57,1	60
10:00	91236	23675	1110,1	74,4	1532	10,6	42,3	58,5	60
10:01	86408	21181	1129,9	74,4	1394	10,6	35	53	60
10:02	81252	17794	1144,6	74,4	1265	10,6	32,4	49,4	60
10:03	76490	14693	1164,9	74,4	1138	10,6	29,1	80,9	60
10:04	73480	9882	1203,5	74,2	1057	10,6	22,5	42,4	60
10:43	58912	3206	1259,8	75,9	737	10,7	12,8	35,7	60
10:45	58678	3432	1258,4	76	728	10,7	14	36,7	60
13:51	59852	1629	1126,8	80,4	772	10,7	46,6	100	60
13:55	54208	2411	1097,5	80,4	667	10,7	0	0	60
13:56	52114	2144	1095,2	80,2	630	10,7	0	0	60
13:57	50106	1885	1094,5	80,2	594	10,7	0	0	60
14:36	44950	120	1029,2	78,8	518	10,6	0	0	60

14:37	45272	141	1026,9	78,8	523	10,6	0	0	60
14:45	45116	115	1008,4	78,6	522	10,6	0	0	60
14:46	45282	92	1007,2	78,6	524	10,6	0	0	60
15:06	44996	32	968,5	78,5	527	10,6	0	0	60
15:08	45032	23	964	78,5	530	10,6	0	0	60
15:15	45088	10	954,1	78,5	531	10,6	0	0	60
15:16	45124	-4	951,2	78,5	529	10,6	0	0	60
17:11	45310	-204	781,6	79,6	537	10,7	0	0	60
17:38	45024	-287	752,1	80,2	530	10,7	0	0	60
17:39	43280	463	751,4	80,2	501	10,7	0	0	60
17:43	35292	393	754,6	80,2	376	10,7	0	0	60
17:44	33390	749	758,9	80,2	349	10,7	0	0	60
17:45	31302	773	761,9	80,2	320	10,7	0	0	60
17:46	29324	701	762,8	80,2	293	10,7	0	0	60
17:48	25296	584	767	80,4	241	10,7	0	0	60
17:49	23254	506	769,6	80,4	216	10,7	0	0	60
17:50	0	0	785,1	79,9	0	10,7	0	0	60
18:50	0	0	818,6	104	0	10,6	0	0	0

* *W_{energy} stands for measurement of the amount of energy needed in the combustion chamber required to regulate fuel flow, value displayed in Btu/second.*

The general behavior of the MTG during the test, as a function of time, is presented in figure 7, where the history of output power, rotation speed, inlet to compressor and exit turbine temperatures, input amount of energy, and air flow is plotted. Analysis of the graphs shows that the Capstone microturbine responds to load changes rapidly, yet during steps up and down in the MTG real power output, turbine speed follows ramps up and down smoothly to the new operating point. When the load bank resistance is reduced, turbine shaft speed drops smoothly to its new operating point.

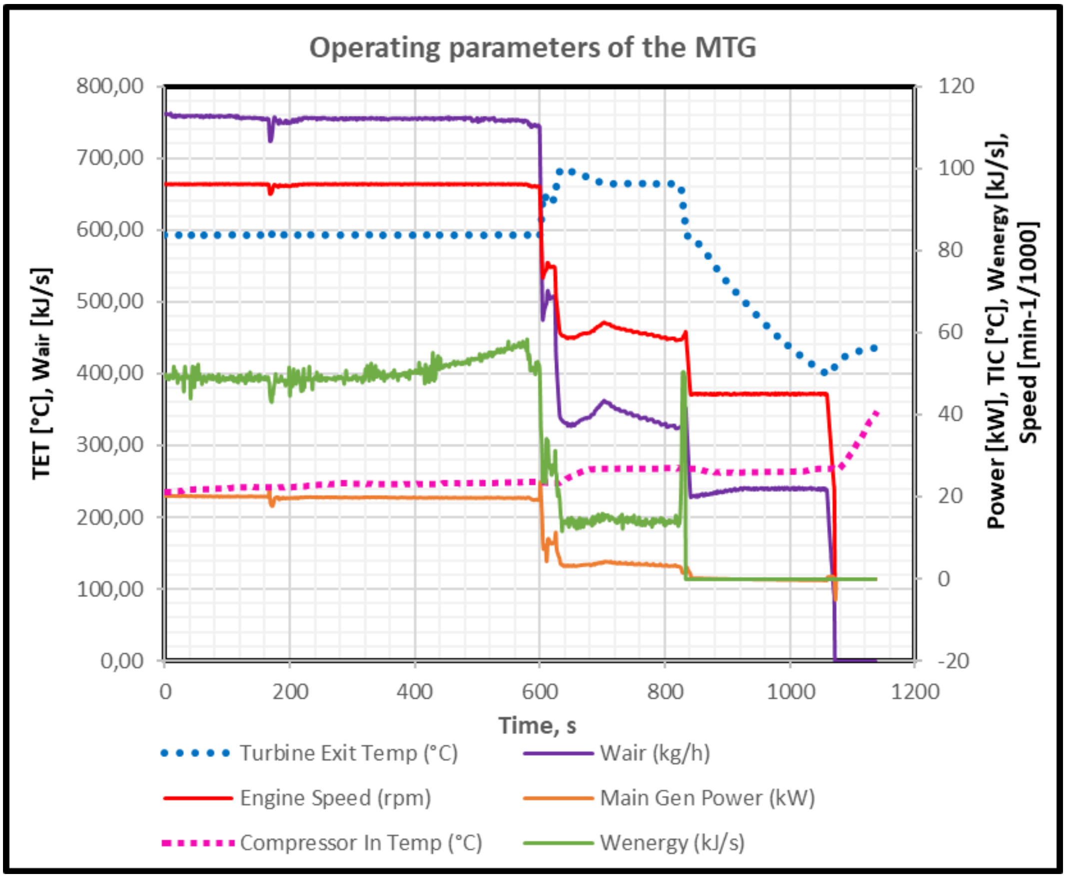

Figure 7: MTG operating parameters as a function of time during test

Microturbine output reacts without sensible delay to the changes in the bank load. The ramp-up rate is observed to be about 8 seconds for 0 to 20 kW. The ramp down rate is about 6 seconds for 20 to 3 kW. As for the fuel energy consumed, it is seen the fluctuation, associated to the mass flow rate adjustments, according to the control dynamics of the fuel valve and to the changes in fuel LHV and density. The variable speed control of the MTG relies on a system that sense load and optimize speed.

Considering the heat value given by the chromatographic analysis of the LPG, the energy flows are converted to fuel flows, which allows to approximate also the air/fuel ratio. The variation of these magnitudes is shown in the figure 8.

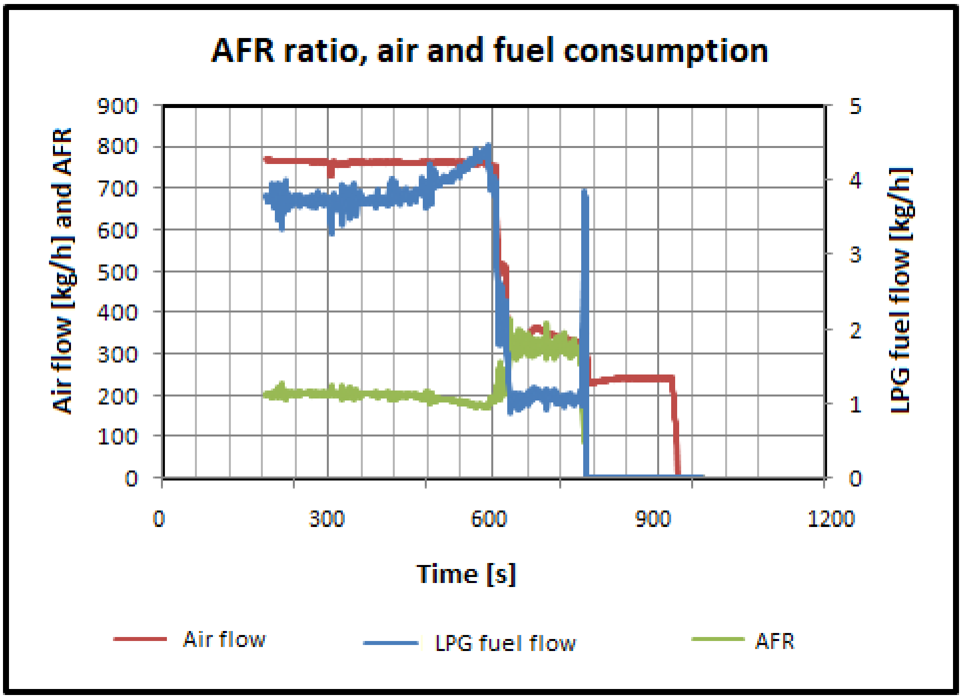

Figure 8: MTG air and fuel consumption, and calculated air/fuel ratio as a function of time during test

An estimate of the MTG efficiency is made by relating the power made by the engine generator and the equivalent energy content of the fuel, as is shown in figure 9.

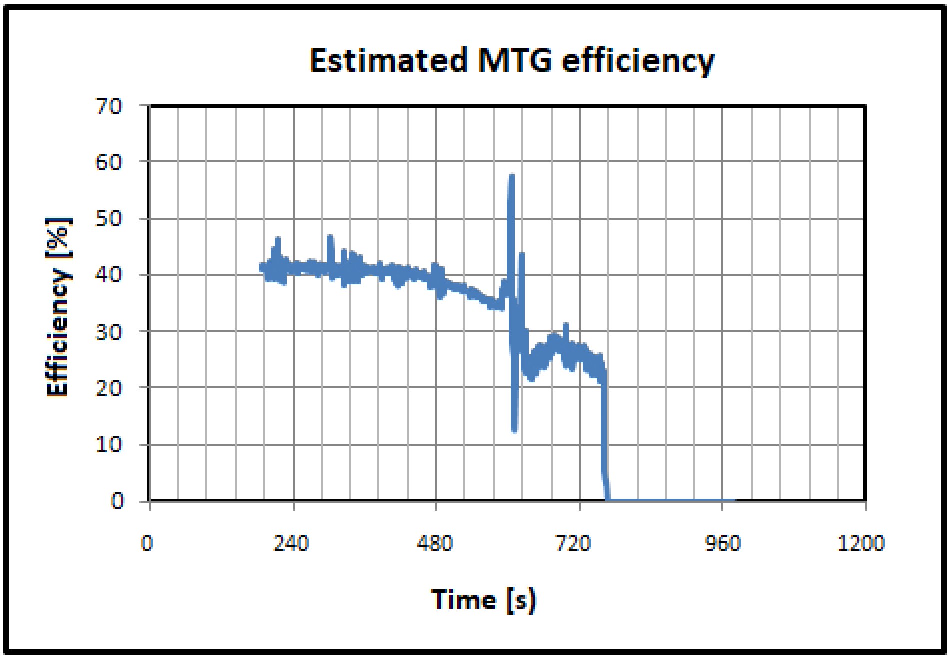

Figure 9: MTG efficiency calculated with the information logged by the controller

Microturbine generator exhibits the variation of rotational speed versus power output described in figure 10 by the experimental values and the adjusted trend line.

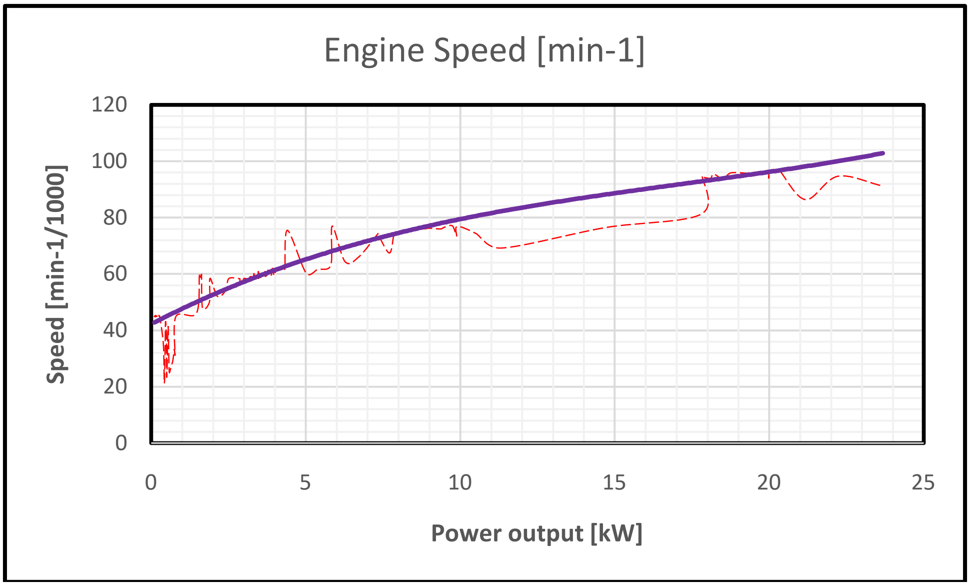

Figure 10: MTG rotational speed as a function of power output

IV. Results of the Electrical Energy Generated

The quality of the energy generated could be influenced by the quality of combustion process of the fuel. MTG with the Capstone microturbine meets the specifications demanded for class G1 generators, in terms of frequency and voltage deviations during transient processes. Observation of the voltage at the load banks during the test showed a small sensitivity to load level. There is little change in the balance of the three-phase voltages. There is no discernable pattern to the changes in the bus voltage; all three phases respond equally to the load changes.

V. Conclusions

Microturbine pilot test was carried out to determine performance characteristics, and to assess the possible inconveniences of using the particular high-butane-content LPG. To achieve the technical goals, it was considered a short test based on a two-step sequence of loads. The main conclusion drawn from the study is that, under the scope of this study, the output of the turbine generator was satisfactory, showing its adaptability to the change in fuel. The limited amount of testing done here restricts the applicability of these conclusions to the specific type of LPG used. Cold and warm starts performed well. The estimated efficiency of power generation appeared to be unchanged, as compared to the values indicated by the manufacturers.

It can be stated that, based on the short test carried out, gas turbines are an advantageous alternative to the use of reciprocating engines, due to their adaptability to the fuel, their low noise and vibration levels, their compact structure and their efficiency close to that of the diesel engine. The tests showed a higher-than-expected performance and it is about to find out with the supplier how close this value is, since in the literature itself a performance of more than 30% is not expected, while the conducted test showed an efficiency close to 40% for 66% of the load. It is yet to be proven.

Gas turbines are an excellent alternative and their technology is very mature for generation and cogeneration standalone applications; in the commercial and industrial sectors, microgrid power parks, remote off-grid locations, presenting only the defect of greater starting time (close to 2 minutes, value obtained from the literature).

References Références Referencias

1. ECOPETROL, “Consultancy to Determine the Schemes for Use of Derived Liquid Petroleum Gas Surplus for Electricity Generation in Oil Fields”, April 18, 2013, Bogotá.
2. National Fire Protection Association. NFPA 58:2011. Liquefied petroleum gas code. 2011.
3. Rosa do Nascimento, et al. “Micro Gas Turbine Engine: A Review,” Federal University of Itajubá, Brazil, 2014.Development of Ceramic Gas Turbines in Japan. Techno Japan. Vol. 30, Nº 11, pg. 10-22. Tokio, 1997.
4. Oyakawa K. Development of Ceramic Gas Turbines. JICA. Tsukuba, 1994.
5. Itoh T., Kimura H. Status of the Automotive Ceramic Gas Turbine Development Program. Artículo ASME 92-GT-2. ASME Journal. New York, 1992.
6. Nishiyama T., IWAI M. Status of the Automotive Ceramic Gas Turbine Development Program, Year

Four Progress. Artículo ASME 95-GT-447. ASME Journal. New York, 1995.
7. Nishiyama T., IWAI M. Status of the Automotive Ceramic Gas Turbine Development Program, Year Five Progress. Artículo ASME 96-GT-36. ASME Journal. New York, 1996.
8. Capstone Turbine Corporation, Capstone Low Emissions Microturbine Tecnology, White Paper, USA, 2000. Capstone Turbine Corporation, Capstone Microturbine Model 330 System Operation Manual, USA, 2001.
9. Capstone Turbine Corporation, Capstone Microturbine Product Catalog, USA, 2012: http://www.capstoneturbine.com/prodsol/products/, consultado el: 20/026/2014.
10. Ho, J. C., Chua, K. J. and Chou, S. K., 2004, Performance study of a microturbine system for cogeneration application, Renewable Energy, pp. 1121-1133.
11. Wang, W., Cai, R., Zhang, N. (2004). General characteristics of single shaft microturbine set at variable speed operation and its optimization. Applied Thermal Engineering, 24(13), 1851-1863. doi:101016/japplthermaleng200312012.
12. Bayar, T. Microturbines take on the market. Cogeneration & on-site power production, pp. 21-24, October 2015.
13. González, N. Y., Cusgüen, C., Mojica-Nava, E., Pavas, A. Estrategias de control de calidad de energía en microrredes rurales. UIS Ingenierías, vol. 16, no. 2, pp. 93-104, Julio-diciembre 2017. Doi: https://doi.org/10.18273/revuin.v16n2-2017009.
14. 2010 Capstone Turbine Corporation. 0911 C30 Natural Gas Data Sheet CAP135 | Capstone P/N 331031E. http://www.capstoneturbine.com/docs/datasheets/C30%20NatGas_331031E_lowres.pdf.