The Status of Experimental Investigations on the use of LPG for Generator Sets in Colombia

2016-01-0880

Published 04/05/2016

Carlos Alberto Romero, Ricardo Acosta, and Juan Lopez
Universidad Tecnologica de Pereira

CITATION: Romero, C., Acosta, R., and Lopez, J., "The Status of Experimental Investigations on the use of LPG for Generator Sets in Colombia," SAE Technical Paper 2016-01-0880, 2016, doi:10.4271/2016-01-0880.

Abstract

It is the aim of the present paper to communicate some preliminary results of the research in progress related to the introduction of LPG as a supplementing fuel for the Colombian power grid supply.

Most of the power units operating in Colombian oil wells are running on Diesel fuel and natural gas. Other fuels like LPG, heavy and dual fuel have received attention in recent years, due partially to the necessity to relieve the national overall petroleum dependency problem, and also because of the availability of a sizable amount of LPG derived from natural gas purification.

In an effort to assess the use of LPG as a fuel alternative to Diesel and natural gas in oil wells, a field study has been carried out. The study focused on the overall performance parameters related to engine operation such as power output, engine efficiency, exhaust emissions, load change response, and noise levels, while running with liquefied petroleum gas obtained in Cusiana, characterized by the presence of butane, pentane, and heptane at concentrations of up to 40%. Seven generator sets spanning the power range from 100 to 1300 kW, coupled to a resistive load bank and instrumented for low speed data and emissions, were tested following a designed experimental procedure that combines starting, steady state, and transient loads. Five of the units tested are originally designed to run on natural gas, while the other two, Diesel based, have been converted to dual-fueled (Diesel/LPG). Neither modifications, nor regulations were made to the base engines, except for those required by the LPG fuel system.

The course of selected performance parameters in the tested engines fuelled with LPG and Diesel/LPG blends is described in this document. The analysis of test results and particularly the overall dynamic behavior of the engine under steady-state and transient operation have been made. Although with the use of LPG a slight reduction in engine performance as compared with the base fuel (either CNG or Diesel) is observed, both in steady state and transient conditions, values of output power, speed fluctuation, emissions, noise levels, and exhaust gas temperatures remained under acceptable levels.

Introduction

The major Refinery in Colombia produces several grades of Gasoline, Kerosene, Diesel and Fuel Oil as the most economical valuable products. From the total sales of the major Refinery in Colombia, LPG represents around 7%. Infrastructure is being developed to move the LPG to market, and projects are under various stages of development to promote the utilization of LPG for power generator sets in processing plants, pipelines, and compression facilities, where there is a high demand for natural gas and Diesel fuel to run them. A solution to reduce the fuel costs is to substitute totally or partially the natural gas and Diesel engines, to burn LPG. Colombia is currently a slight net exporter of LPG, an increasing part of which is obtained as a byproduct of natural gas purification in known fields as Cusiana. Also, the government plans expansions in both gas processing and refinery capacity that could significantly add to LPG production by 2014. In response to this fact, some energy suppliers have conducted experimental tests on CNG power generators converted to LPG fuel, whereas others have started to introduce bifuel Diesel/LPG power generators.

Some works to evaluate the operation of power generators when using LPG from Cusiana wells preceded the study presented in this paper:

- The Institute of Planning and Promotion of Energy Solutions for non-interconnected areas, IPSE, conducted a study in Timbiquí city, after which it was concluded that LPG generation is competitive with respect to Diesel generation in performance and economy. However, the study pointed out that the results were not obtained for all the required load points.

- The IPSE monitored for a period of seven months (a total of 1461 hours) the operation of a brand 120 kW GENERAC power generator connected to the electrical grid of Fort Island, in the Department of Córdoba. Because of the LPG prices in the island, it was concluded that the use of this alternative fuel in areas not interconnected, with high transportation costs, was not economically feasible.
- SURPETROIL S.A. conducted generation tests with Cusiana LPG in La Hocha Field, in the Department of Casanare. The generator used was a CETEC CGN 505, with a 410kW V222TI Doosan spark ignition engine. The generator was run with different mixtures of LPG and CNG, keeping the 10,5 original engine compression ratio. High knock intensity was observed for the 87/13 and 50/50 LPG/CNG mixtures at 1800 rpm. After reducing the compression ratio of the engine to 7, the performance of the engine fuelled with LPG was satisfactory, but the efficiency reduced to 10%.
- SURPETROIL S.A. subjected to an eight hour test a CETEC CGN 505 power generator in Campo Corcel, in the Department of Casanare. The compression ratio of the engine was increased to 8,7, along with other modifications. It was observed a satisfactory performance of the engine fuelled with LPG, supplied from Campo Corcel (Petrominerales) under a constant load of 300kW.

Along with the increasing interest in using LPG for power generators, the necessity of conducting a campaign to disclose the performance behavior of power generators was concluded after the study “Consultancy to Determine the Schemes for Use of Derived Liquid Petroleum Gas Surplus for Electricity Generation in Oil Fields” carried out by ESEI S.A. [1]. This study found that the best alternative for exploitation of LPG surplus left by the production plant Cusiana was destine it for electricity generation in oil fields of 400 kW minimum installed capacity, those that might be declared not regulated under present Colombian legislation. The same study called attention to the high percentage of butane in the composition of the Cusiana LPG.

Contrary to the attention paid to the study of engine behavior when using propane in delivery transport in different countries, there are not so many studies issued on the use of LPG in power generation based on piston engines. Companies like Cummins and Caterpillar, among others, design some of their engines to operate on LPG with propane/butane compositions very different from those of Cusiana LPG. More related to the use of LPG for power generation are the experimental and research works on spark ignition engines with output power below 180 kW, operating on LPG. Some of these works were covered in the review carried out by Lawankar and Dhamade [2].

The summary of experiences and tests conducted, as well as the uncertainties associated with the impact of high butane content of Cusiana LPG (to date, there has not been reported any experimental tests related to the performance of generator sets fuelled with LPG from Cusiana), encouraged our research group to continue with feasibility studies under controlled loads, monitoring the thermal and dynamic performance of power generators.

Six different power generators with distant rating power were evaluated judging about their power output, step response, power quality, fuel consumption, and emissions.

The work here presented refers to that evaluation study, and is organized as follows: first, a brief scope of the use of LPG in combustion engines is given, with special emphasis on the fuel description and fuel system particularities when using LPG. After that, this paper describes the engines tested, experimental procedure and constraints. Next, the test program is described, followed by a summary of the results. Finally, there are presented the main conclusions of the work.

Particularities in the Use of LPG in Internal Combustion Engines

Comparison of CNG and LPG Gaseous Fuels

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 composition of LPG used as an engine fuel varies from almost pure propane to almost pure butane. In the United States, the industry has a propane standard known as HD-5, which requires a minimum propane content of 90%, volume based, and a propylene content of less than 5%. Propylene does not occur in LPG obtained from natural gas processing plants but is found in the LPG resulting from oil refinery operations.

Several of the key defining characteristics of gaseous fuels with respect to use in internal combustion engines are listed in table 1.

Table 1. Technical data for propane, butane, and natural gas [9].

Properties of		CNG	Propane	Butane
Boiling point of liquid at atmospheric pressure	ºF	-258,7	-44	32
Specific gravity of vapour (air =1)		0,6	1,53	2,00
Specific gravity of liquid (water =1)		0,6	0,51	0,58
Calorific value @ 60 ºF	BTU/cuft	1012	2516	3280
	BTU/lb		21,591	21,221
Latent heat of vaporization	BTU/gal	712	785,0	808,0
Liquidweight	lbs/gal	2,5	4,24	4,81
Combustible limits	% of gas in air	5 - 15	2,4 - 9,6	1,9 - 8,6
Amount of air required to burn 1 cuft. of gas	cuft	9,53	23,86	31,02
Ignition temperature in air	ºF	1200	920 - 1020	900 - 1000
Maximum flame temperature in air	ºF	3568	3595	3615
Octane Number		120	97	90
Wobbe index			2034	2319

As shown in table 1, the volumetric air/fuel ratio for CNG is 9,53. One cubic meter of fuel is required for every 9,53 cubic meters of air charged. In other words, because the fuel gas must displace air, switching a gasoline engine to CNG results in a reduction of about 9,3% in the amount of air that enters the cylinder and a corresponding reduction in power. For propane, the gas displacement effect is only about 4,0%. LPG must be calibrated for a lower volumetric fuel flow rate at a given load; due to the lower octane number, to prevent combustion knock, conversions from CNG engines to LPG require the engines to be de-rated, which is accomplished by reducing compression ratio, lowering turbocharger boost pressure, or foreseeing power reduction. Because of the octane limitation, an LPG engine would be expected to have somewhat lower fuel efficiency than a CNG engine operating in similar service.

Most recently, LPG from Cusiana has emerged as a major source, and the industry knows that its composition differs substantially from HD-5 used in United States. The potential problem with LPG from Cusiana Field is the relatively high knocking tendency. The presence of butane, pentane, and heptane at concentrations of up to 40% can lead to increased engine knock, which can severely damage the engines. Analysis of Cusiana LPG is presented in table 2.

Table 2. Composition and physical properties of Cusiana LPG (*)

Compositional Analysis of LPG to C12+			
Sampling Location		**ALSABANA**	
Cylinder Number		**CLM009**	
Sampling Conditions		**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 means less than 0,005.			
CalculatedWhole Gas Properties			
Gas Gravity	1,6272	(Air = 1 @ 14,73 psia& 60°F)	
Whole Sample Mole Weight	47,13	g mol^{-1}	
Ideal Gas Density	1,9831	kg m^{-3} @ 14,65 psia, 60°F	
Ideal Gross Calorific Value	2665,7	BTU·ft^{-3} @ 14,65 psia, 60°F	
Ideal Net Calorific Value	2454,5	BTU·ft^{-3} @ 14,65 psia, 60°F	
Pseudo Critical Press.	598,7	psia	
Pseudo Critical Temp.	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 Gross Calorific Value	2722,4	BTU·ft^{-3} @ 14,65psia, 60°F	
Real Net Calorific Value	2506,6	BTU·ft^{-3} @ 14,65psia, 60°F	

* Results of the Chromatographic test performed by Equion, Colombia, November 12, 2012.

LPG and Bifuel Systems of the Tested Engines

Fuel Delivery System Design

The primary need identified by the fuel delivery team was to collect fuel from the storage tanks and deliver this fuel to the engine in required fuel rates at the desired phase of LPG throughout the delivery and intake process. The selection of the phase of the fuel is an important decision in the project; the technical options for the fuel delivery system includes carburetion, single point vapor injection, single point liquid injection, vapor port injection, liquid port injection, and direct cylinder injection. Several advantages and disadvantages can be attributed to each of these fuel delivery options. Although other issues exist, the major consideration is whether to use vapor or liquid injection. Of all the alternative fuels, LPG possesses vapor liquid characteristics such that, by proper design, either a liquid or a vapor system may be adapted for typical ambient temperatures.

Liquid injection offers the advantages of higher potential efficiencies due to less displaced air and charge cooling in the engine ports and cylinders. The major disadvantages include the higher operating pressures, the need to provide for excess fuel recirculation, and the possible need for fuel cooling. Liquid injection requires relatively low temperatures (less than 315 K) and high pressures (about 1,3 MPa) in the fuel system to maintain the fuel in a liquid state, which makes it necessary the use of high pressure LPG pumps. In addition, working on-site temperatures can cause the liquid fuel to vaporize in the fuel lines, resulting in metering, control, and safety problems.

Of the mentioned available technical options, the power groups studied under the scope of this project, comprised carburetion, single point vapor injection, and vapor port injection, except for the tested 100 kW and 1200 kW power units, fuelled with liquid LPG. Sequential vapor injection sceheme was implemented in the largest 1200 kW unit; carburetion was used in the CNG units converted to LPG, as well as in the bifuel Diesel/LPG factory arranged units.

Bifuel Systems

The cofiring of LPG in a Diesel engine is not new technology. A Diesel engine cannot operate on 100% LPG, because the heat generated during compression is not sufficient to ignite this fuel. To create ignition in bifuel engines, a small amount of Diesel fuel must be injected. Cylinder temperatures are high enough to ignite the Diesel fuel, and the flame created reaches a temperature sufficient to ignite LPG. With most designs, the Diesel fuel is delivered using the injectors that already exist on the engine. Additional components are installed to deliver LPG into the combustion chamber. The bifuel control systems monitor LPG pressure, manifold pressure, temperatures, and engine vibration to control fumigated gas injection [10]. A significantly larger amount of fuel is precharged in the cylinder prior to injection of Diesel fuel.

It is important to understand the fuel characteristics relative to both knock and compression ignition characteristics for bifuel operations. A Diesel engine fitted with a bifuel system relies on compression to ignite diesel fuel, which, in turn, provides the spark to ignite the gaseous fuel. It is in this sense that both octane (knock) and cetane (ignition delay) performance are relevant characteristics of the subject fuels.

No major changes to the engine were attempted since these changes could disrupt the fine balance between performance, efficiency, and emissions. Performance of the engines is limited to the levels of factory based engine specifications.

Experimental Facilities and Procedures

Alsabana campus in Mansilla, an LPG storage plant, was the facility that hosted this evaluation project. The primary need identified by the working team was to safely store a sufficient quantity of LPG to carry out the test campaign uninterruptedly. The location and basic arrangement of the fuel supply system allowed LPG to be drawn from tank toward the engine intake system, through safety relieve and reduction pressure valves, so that fuel supply lines could travel far enough away from the hottest engine spots. Valve design prevented possible fuel leaks. The fuel supply system featured in-line manual shut-off valves as well as an automatic shut-off valve operated electronically by the ignition switch. The storage pressure ranged between about 50 and 90 psia during the tests. The power generation groups were connected to an Avtron 1000 kW capacity electrical resistance load bank, with a manual load setting. A schematic of the general layout of the test facility can be followed in the figure 1. In fact, the vaporizer was used only for the largest 1300 kW rated power JAE R16V300-H12 generator set; the remaining five units were fuelled with liquid LPG.

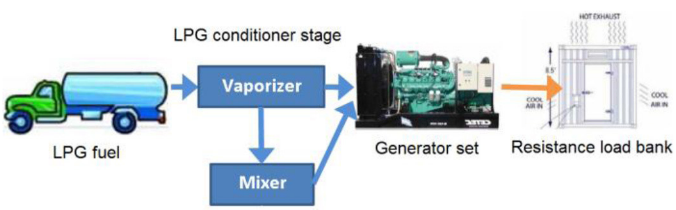


Figure 1. General layout of the test place.

The specifications for the generator units subject to test are presented in table 3.

To carry out the assessment of electrical, thermal, emissions, and operational performance of power generation systems fuelled with LPG, it was structured a field protocol summarized in the flow diagram of Appendix 1. To devise the protocol, some principles and guidance contained in ISO 15550 [3], ISO 8528 [4], ISO 3046 [5], and ISO 8178 [6] standards were taken into consideration.

Irrespective of the power generator to be evaluated, the field protocol comprised activities such as setup or pretest activities, scheduled load tests (a stepwise sequence of designated loads for a sufficient time), mechanical and electrical performance assessment, electrical efficiency, atmospheric and acoustic emissions tests conducted during two complete test runs at each of selected power command settings (startup, warm-up, idle, 25,50, 75, and 100 percent of full load). The flow diagram in Appendix 1 explains procedures, runs, conditions, and parameter classes evaluated during each phase of the test.

Each test begins with the evaluation of the cranking performance, followed by a preconditioning warming up of the engine at the rated power used in the test cycle to stabilize the engine parameters. It was foreseen also a period of stabilization in the test modes included to minimize point to point influences. Every power generator was operated in each mode a minimum of 10 min each point.

The engine load, intake air temperature, exhaust temperature, fuel and air flow were calculated within the final part at each mode after the engine had stabilized. To follow the field tests, each generator set was instrumented to measure the following parameters at each of the power command settings: real power, apparent power, reactive power, power factor, voltage total harmonic distortion, frequency, voltage, and current. In addition to energy measurements, fuel consumption at site ambient conditions (relative humidity, ambient air temperature, and barometric pressure) was estimated.

Table 3. Specification of the Engines of generator sets studied.

Engine	CETEC GV222TI	Waukesha F3521GSI	JAE R16V300-H12	CUMMINS 6CTA8.3-G2	CUMMINS 6CTAA8.3-G1	QSX15 DFEH
Cylinder number and cylinder block configuration	12 V cylinders, turbocharged, aftercooled	In-Line 6 cylinder, turbocharged, aftercooled	16 V cylinder, naturally aspirated	In-Line 6 cylinder, turbocharged, aftercooled	In-Line 6 cylinder, turbocharger, aftercooled	In-Line 6 cylinder, turbocharged, aftercooled
Displacement, l	21,927	57,7	430	8,3	8,3	15
Power output, kW	369	550	1300	107	213	507,3
Speed, min^{-1}	1800	1200	600	1800	1800	1800
Bore/Stroke, mm	128/142	238/216	300/380	114x135	114x135	137/169
Mean piston speed, m/s	8,52	8,64	7,6	8,1	8,1	10,1
Compression Ratio	8:1	8:1	9:1	8,5:1	16,8	17:1
Brake mean effective pressure, bar	11,21	9,39	5,45	8,6	17,17	17,995
Fuel	LPG Cusiana	LPG Cusiana	LPG Cusiana	LPG Cusiana	Bifuel (37,11 % substitution)	Bifuel (29 % de substitution)

Not getting into details, the test protocol begins by performing the engine cold startup with the spark plugs (Diesel fuel injectors) installed, and recording the crankshaft speed, and engine vibrations (this is required to assess the startability of the engine for the studied fuel and also to have an appraisal of the dynamical behavior of the engine during cranking). After that, the engine is kept running under the lowest load allowed by the engine instructions, until the coolant and oil temperatures recommended by the manufacturer have been reached, recording the crankshaft speed, engine vibrations, and other engine performance parameters, required for the evaluation of thermal, emissions, and operational performance of the power generation system, during the warm-up (this is required to evaluate the thermal response of the engine). Once the engine has reached the thermal operational state, the first 25% of full load (the full load limited by the knock occurrence, either the load recommended by the operator) is set. After this, two sets of ambient conditions (relative humidity, ambient air temperature, and barometric pressure) are recorded, at the beginning and at the end of test run; the power unit is operated at 25% of full power, and after a stabilized period, two sets of the crankshaft speed, engine vibrations, engine noise, electrical power, fuel and air flow rates, exhaust gas, cylinder head and coolant temperatures, fluid pressures, and other engine performance parameters, required for the evaluation of thermal, emissions, and operational performance of the power generation system are recorded. As the protocol continues, the procedure is repeated through 50, 75, and 100 percent of full load, as summarized in the flow diagram, Appendix 1.

After conducting the described test procedure, a full-load test was performed for every engine to evaluate the performance of the power generation along an extended period, and to estimate the sensitivity of the engine performance to the changing ambient conditions and fuel composition (propane/butane in LPG), which was presumed to change as the fuel is consumed from the tank. The full load test served also to calculate the fuel efficiency of the power generation system at full load.

Data Acquisition

Depending on each specific power generation system, proprietary and customized National Instruments based instrumentation were used to acquire data for determining the performance, efficiency, and emissions characteristics of each power group configuration. Engine power output was measured with a FLUKE 434/PWR energy meter connected to the generator power output. The engines were outfitted with accelerometers to measure vibration, and magnetic pickups to record the speed of engine crankshaft. Flow meters were attached to the fuel lines to measure the mass flow rate of fuel. Emissions equipment was used to determine engine-out hydrocarbon, carbon monoxide, and nitrogen oxides emissions. In addition thermocouples were installed to measure temperatures in the intake, exhaust, coolant and oil fluids. The system was setup to log data collected by the operator controller system, high speed pressure data in one of the engines of the 16 cylinders JAE engine, rpm, and fuel consumption data.

The measured fuel flow rates were used in conjunction with the LHV of the fuel to determine energy input to the engines. Over the course of the field demonstration, a series of exhaust gas measurements were obtained to evaluate the effect of LPG and bifuel operation on air emissions. Sample probes were installed on each engine to provide access for emission sampling. Measured emissions NOX, O2, CO, and HC were converted to a g/kWh basis for comparison.

A summary of the instrumentation used is listed as follows:

LPG fuel flow measurement, fuel flow meter vortex type OPTISWIRL 4070, measurement range: 12 a 180 m3/h.

Electric generation quality, three phase electrical power quality analyzer FLUKE 434/PWR, measurement range: -Vrms (AC+DC):1-1000 V; frequency 40-70 Hz.

Emission composition. exhaust gas analyzer BACHARACH model 300, AVL HGA 400, and CUBIC gasboard-3100p.

Air intake flow, hot wire anemometer LT lutron AM4204, measurement range: 0-30 m/s.

Intake manifold pressure, pressure transmitter VEGABAR14, measurement range: 0-6 bar kPa.

Intake manifold temperature, J type thermocouple, measurement range: 0-1000 °C.

Coolant temperature, J type thermocouple, measurement range: 0-1000 °C.

Exhaust gas temperature, J type thermocouple, measurement range: 0-1000 °C.

Metal cylinder head temperature, J type thermocouple, measurement range: 0-1000 °C.

Detonation occurrence, Knock sensor KS39.

Ambient temperature and humidity data logger, Amprobe TR300; temperature measurement range: -20-70 °C, humidity measurement range: 0,0 □ 100,0%.

Data acquisition system NI cDAQ-9172.

Noise measurement, sound level meter UEI DSM 100, measurement range: 30-10000 Hz, 35-130 dB; 30-10000 Hz, 35-130 dB; 30-10000 Hz, 35-130 dB.

Metal temperature, Infrared camera Fluke Ti32, measurement range: 0-600 °C; infra-red thermometer Fluke FLK-568, measurement range: 0-800 °C.

Engine compression, analog compression gauge, measurement range: 0-300 psi, 21, kg/cm^2.

Diesel fuel consumption, Digital Meter Fill-Rite 820, measurement range: 7,6-75,7 lpm

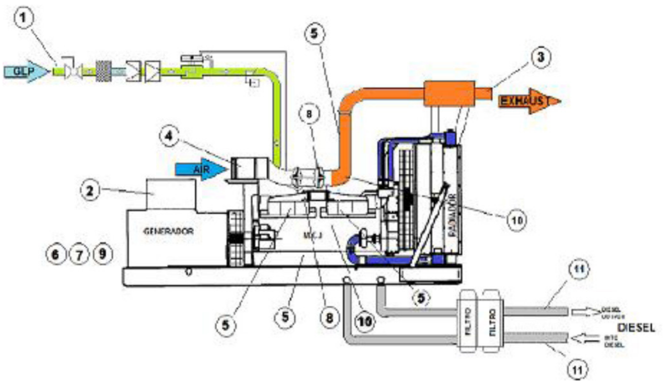


Figure 2. Schematic of the base instrumentation used during the test of generator sets. 1. Fuel flow meter; 2. Three phase electrical power quality analyzer FLUKE 434/PWR; 3. Exhaust gas analyzer; 4. Hot wire anemometer; 5. Exhaust gas temperature sensor; 6. Ambient temperature and humidity data logger; 7. DAQ system; 8. Infra-red camera; 9. Sound level meter; 10. Engine temperature sensor; 11. Diesel fuel meter.

Figure 3. Details of the base instrumentation used during the test of generator sets.

Throughout the test campaign, the research group paid special attention to the data recorded by proprietary controllers in each power generation unit. Most of the controllers continuously monitors a variety of engine and generator parameters, including intake air and exhaust gas temperatures, engine coolant temperature, intake manifold temperature and pressure, output power, engine speed, and engine vibration at each cylinder. In bifuel systems, the controller monitors LPG supply pressure, providing also the metering of LPG to be supplied to the engine under different load conditions. In general, this feature is designed to allow the engine to operate with the largest amount of LPG possible at different loads. At low loads (up to 30% approx.), LPG flow is stopped because it becomes difficult for the engine governor to maintain a constant engine speed if bifuel is being used. Diesel fuel flow was measured with fill-rate fuel totalizer.

The general instrumentation layout can be followed in the schema of figure 2. The resistance load bank has not been represented. To be illustrative, a sample of the instrumentation used is compounded in figure 3; in the snapshots of the bottom it can be seen the Avtron resistance load bank used during the test of the JAE engine.

Results during the test program

The objectives of the test were to present the experimental results, as well as to provide overall performance and emissions results. In addition to the overall project goals, the technical goals included the assessment of bifuel system operation. In general, all engines were tested according to the common field protocol without major negative perceivable effect.

The summary of the relevant performance parameters of generator sets, fuel consumption, exhaust emissions, and energy quality, during its operation with LPG fuel, is presented in table 4. Efficiency at maximum load is highlighted for Waukesha F3521GSI, and CUMMINS QSX15 DFEH engines. None of the tested engines presented knock during their operation with LPG.

Performance of the Generator Set based on the CUMMINS 6CTAA8.3-G1

Because of the scope of the present paper, not all the results for all the Power units tested can be presented. Instead of that, a summary of the graphical results obtained for the CUMMINS 6CTAA8.3-G1base power unit is presented. An illustration of the generator set tested is shown in figure 4, where the control of the LPG fuel system can be observed.

In the following, a series of performance graphs, all conducted at generator nominal speed are presented in a logical order together with a description and discussion of salient points, to show some partial results of the test campaign, starting with the presentation in figure 3, of the stepwise load schedule. Because of technical problems, the load schedule for the BIFUEL-CUMMINS 6CTAA8.3-G1, could not adjust to the schedule considered in figure 5.

Table 4. Engine Performance Summary

Engine	CETEC GV222TI	Waukesha F3521GSI	JAE R16V300-H12	CUMMINS 6CTA8.3-G2	CUMMINS 6CTAA8.3-G1	CUMMINS QSX15 DFEH
Fuel	LPG Cusiana	LPG Cusiana	LPG Cusiana	LPG Cusiana	Bifuel (37,11 % substitution)	Bifuel (29 % substitution)
Maximum test load, %/kW	100/261	100/497	100/620	100/78,08	100/179,2	100/400
Actual LPG specific power, kW/l	16,83	9,53	3,02	25,66	33,82	16,83
"Derating" %	29,27	9,64	52,31	27,10	15,87	21,15
LPG consumption at max. test load, kg/h	115,38	127,97	251,8	21,0	18,92 kg/h LPG combined with 32,93 kg/h of Diesel fuel	26,68 kg/h LPG combined with 65,32 kg/h of Diesel fuel
Efficiency at max. load, %	17,28	**29,67**	18,823	28,41	26,83	**35,30**
Specific CO emissions, gr/kWh	0,46 < 3,5 (comply)	0,612 < 3,5 (comply)	No reliable measurements because of accidental dilution of exhaust gases with ambient air	17,10 > 5,0 (formally does not comply)	11,06 > 5,0 (formally does not comply, injection parameters must be adjusted)	7,80 > 3,5 (formally does not comply, injection parameters must be adjusted)
Frequency, ± Hz	± 2Hz during transients	< 1 Hz during transients	± 2Hz during warm-up , and higher values during transients	>> 2Hz during transients	High and prolonged deviations during load transients and fuel changes	Good
Voltage, ± V	Normal, except during transients	Good in all load cases	Irregular during warm-up	Not so regular, especially during transients	High and prolonged deviations during load transients and fuel changes	Good in all load cases(a light voltage decrease as the load increases, and high changes during transients)
Transient response	Slow acceptance of full load	For loads above 75 %, the stabilizing time increases	Slowness to accept the load	Poor transient response	Good transient response, sustained fluctuations along all the test	Very good(slight power overshoot during transients)
Noise, dB	102	94	114	104	105	--
Vibrations, mm/s^2	Good	Good	Good	Good	Good	Good
Base line for fuel consumption, l/h	89,4 Nm^3/h at 75% load (with CNG, aprox. 14 MJ/kWh)	5805 BTU/HR x 1000 (1701 kJ/s at 550 kW)	≤ 12MJ/kWh	< 11 MJ/kWh (< 24,3 kg/h LPG)	52 (Diesel)	118 (Diesel)

Figure 4. Generator set based on BIFUEL-CUMMINS 6CTAA8.3-G1

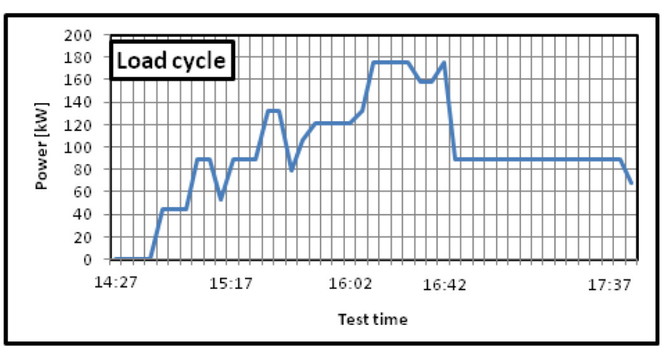


Figure 5. Engine load as a function of time for the bifuel Cummins 6CTAA8.3-G1 generator set test.

Some of the parameters registered during the generator set test protocol are depicted in table 5; among these parameters, the pressure and temperature inside the intake plenum, as well as exhaust gas temperatures are of importance. In the table 5, the fuels and fuel consumption for the corresponding loads are quantified. At full load, the optimum blend of LPG for firing in a diesel engine was found to be 37% Diesel substitution.

The fuel consumption measurements were determined two different ways. The first method relied on diesel fuel meter data and theoretical "Diesel-only" data to estimate fuel savings. When engine was operating in bifuel mode, the actual diesel consumption was measured. The diesel-only curves were used, along with the measured engine load, to calculate what the theoretical diesel-only consumption rate would have been if LPG supply had been off. The fuel replacements were determined by calculating the difference between the calculated "Diesel-only" fuel rate and the measured fuel rate under bifuel operation.

Table 5. Performance parameters of the power group registered by its proprietary controller during the test cycle.

Time	Fuel	Load		MAP	MAT	EGT	Diesel	Substitu-tion
		[kW]/[%]		[psi]	[°C]	[°C]	[kg/h]	[%]
10:16	Diesel	0	0	-0,10	20,56	18,89	-	-
14:47	Diesel	44	25	3,50	29,44	232,22	19,35	-
15:02	Diesel	89	50	8,40	33,89	316,67	30,72	0,00
15:32	Diesel	132	75	13,60	35,00	391,67	40,57	0,00
16:17	Diesel	176	100	19,00	40,00	458,33	52,36	0,00
16:47	Bi-fuel	89	50	8,30	37,22	369,44	13,22	67,41
16:22	Bi-fuel	176	100	19,00	41,67	456,67	32,93	37,11

The LPG consumption rate was converted to an equivalent Diesel rate based on 47500 kJ/kg for the gas and 42500 kJ/kg for the Diesel fuel. Comparison of the fuel consumption in both "Diesel-only" and bifuel operation can be followed in table 6.

Table 6. Fuel consumtion for two particular load states.

Load [%]	Load [kW]	Fuel consumption [kg/h]		
		Diesel only	Diesel in Bifuel	LPG in Bifuel
50	89,00	30,72	13,22	17,03
100	176,00	52,36	32,93	18,92

The relative fuel consumption for two of the load cases can be followed in figure 6.

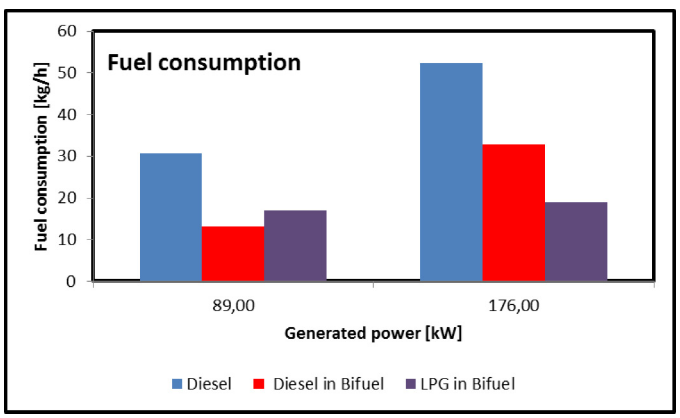


Figure 6. Diesel and LPG fuel consumption during bifuel operation for the 50 and 100% load cases.

The thermal behavior of the engine during the test had the evolution presented in figure 7, where the time history of fuel mixture, engine oil, as well as metallic temperatures is plotted. It is noteworthy the sensitivity of the temperature change of the cylinder head temperatures to the load changes. Though not plotted in the figure 7, engine exhaust gas temperature is one of several parameters the engine control system must monitor to ensure proper engine performance when supplying gaseous fuel to the engine.

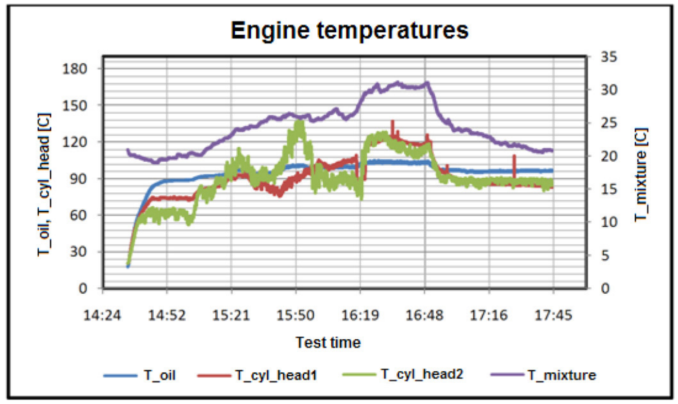


Figure 7. Engine load as a function of time during Bifuel Cummins 6CTAA8.3-G1 generator set test.

Engine Dynamic Behaviour

Engine vibration was monitored on each engine to ensure bifuel operation did not adversely impact engine performance. The supply of Cusiana LPG fuel can alter combustion properties and lead to uncontrolled fuel detonation, engine knock, and excessive vibration. The bifuel control system is designed to ensure that this does not occur by monitoring engine vibration and stopping LPG flow if vibration is detected.

To evaluate the dynamic engine performance, engine vibration and speed engine response were measured with accelerometers placed in the positions observed in the schematic of figure 8. The inductive pick-up was used to study the engine speed. Some of the vibration results for point number 1 are plotted in the graphics of figures 9 and 10, where accelerations can be observed, along with speed response during the test engine transients. Evident are fairly irregular spikes in vibration, associated with rapid changes in load, and possible lack of engine control system tuning. Small fluctuations are observed, even for the engine working solely on Diesel.

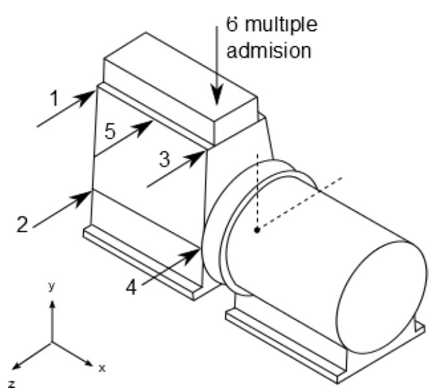
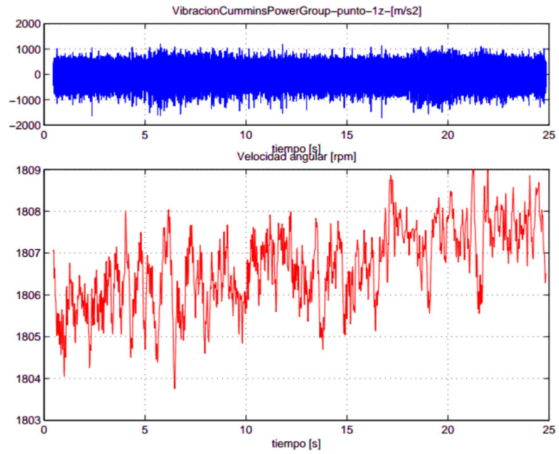


Figure 8. Distribution of accelorometeres placed to observe the engine vibrations.

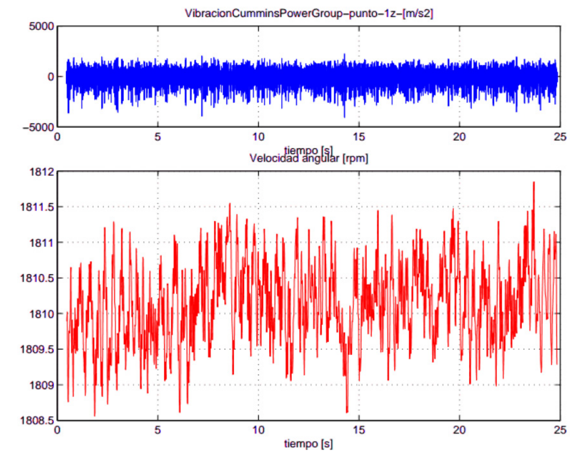
During step type engine transients of load, generator set experimented kind of hiccup and drop back on speed.

In general, engine oscilograms allow concluding, that the engine is not very sensitive to the LPG fumigation. Indeed, vibrations and speed responses are quite similar, irrespective of the composition of the fuel, showing practically the same variability. Probably, this variability can be reduced by tuning-up the engine fuel system, adjusting the engine governor, since this engine has mechanical injection. This is a fact to be taken into account during conversions of Diesel engines to bifuel systems.

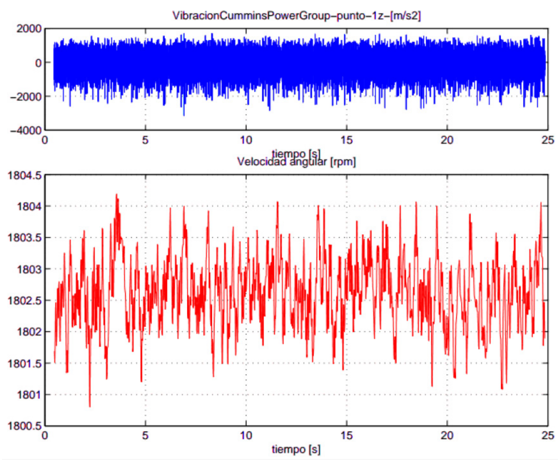
It is observed a reduction in the engine speed as the load demand increases, when the engine is operated in bifuel mode, which impairs the maximum power of the engine.



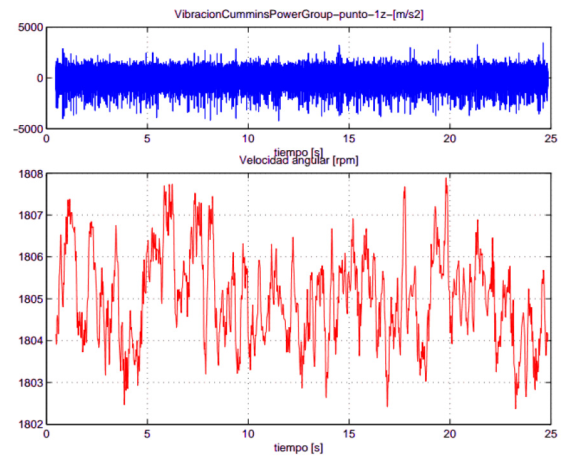
a). Idle



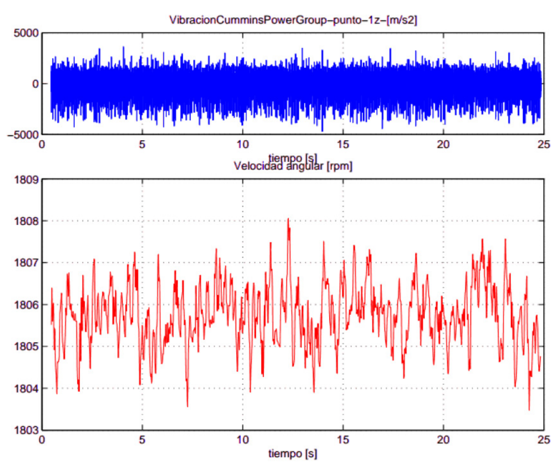
b). 44 kW power (25 % load)



c). 89 kW power (50 % load)

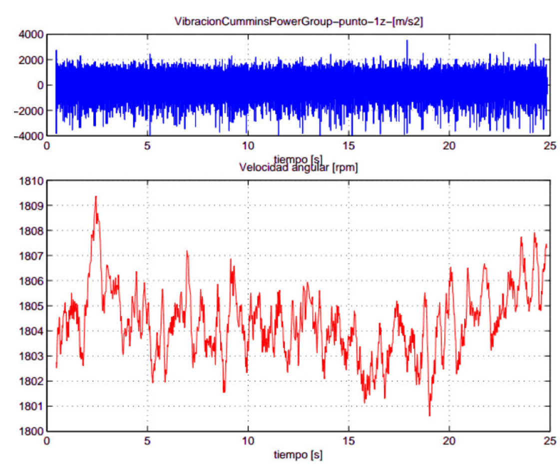


d). 179 kW power (100 % load)



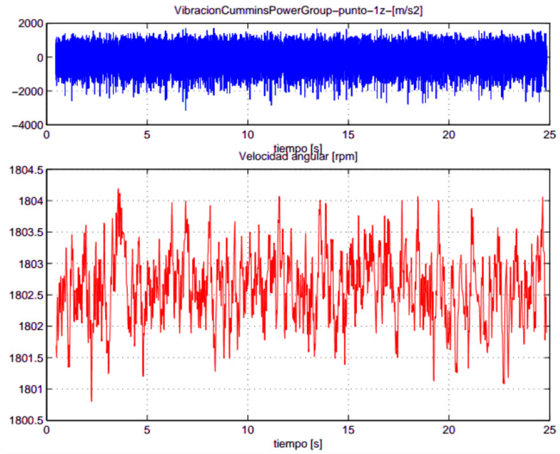
e) 132 kW power (75 % load)

e). 132 kW power (75 % load)

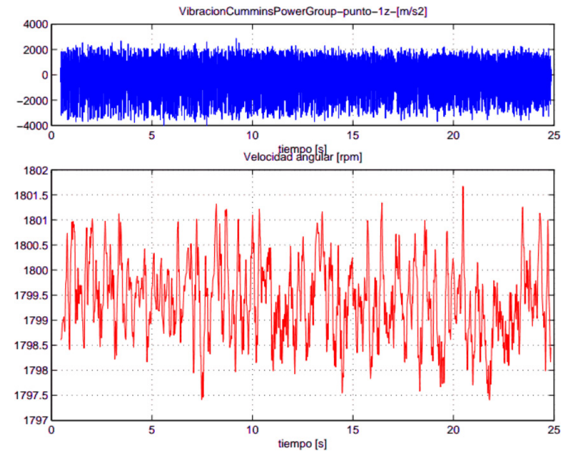


f). 192 kW power (107 % load)

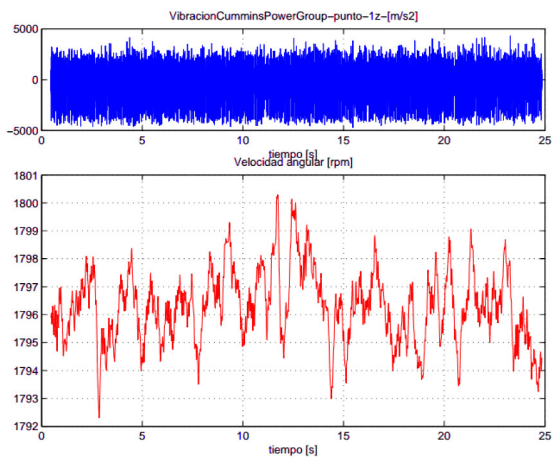
Figure 9. Engine acceleration and speed response of CUMMINS 6CTAA8.3 G1based power unit when working solely on Diesel fuel.



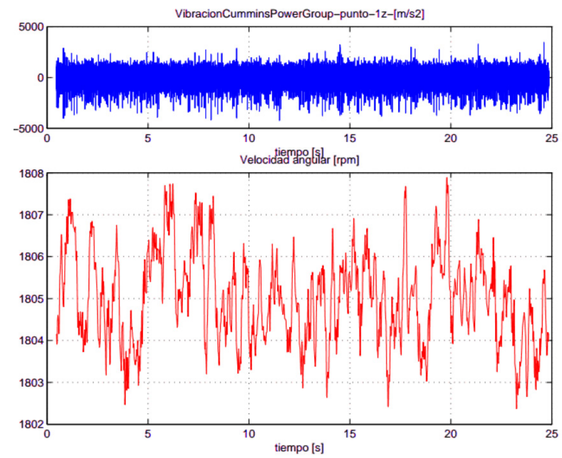
a). 89 kW power (50 % load)



b). 132 kW power (75 % load)



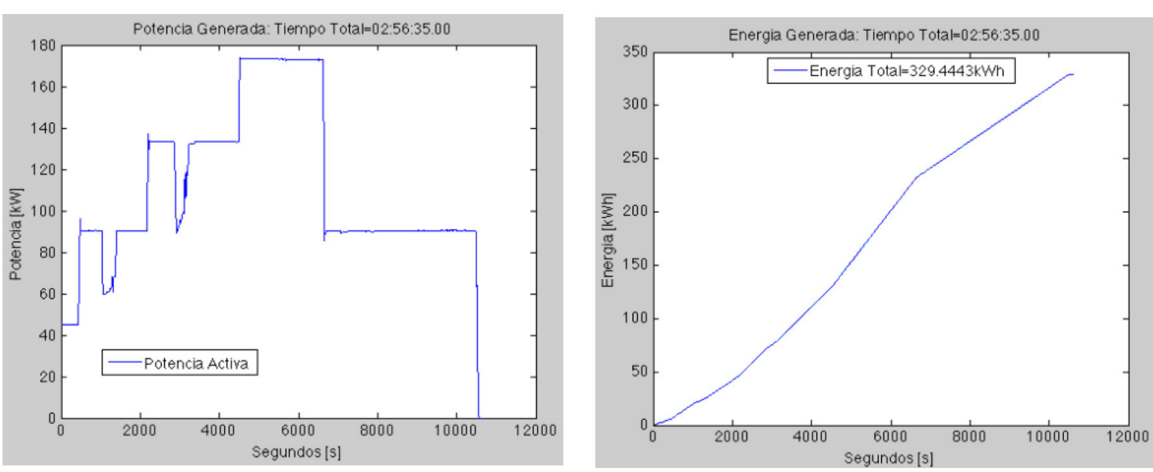
c). 179 kW power (100 % load)



d). 179 kW power (100 % power -Diesel only) - duplicated

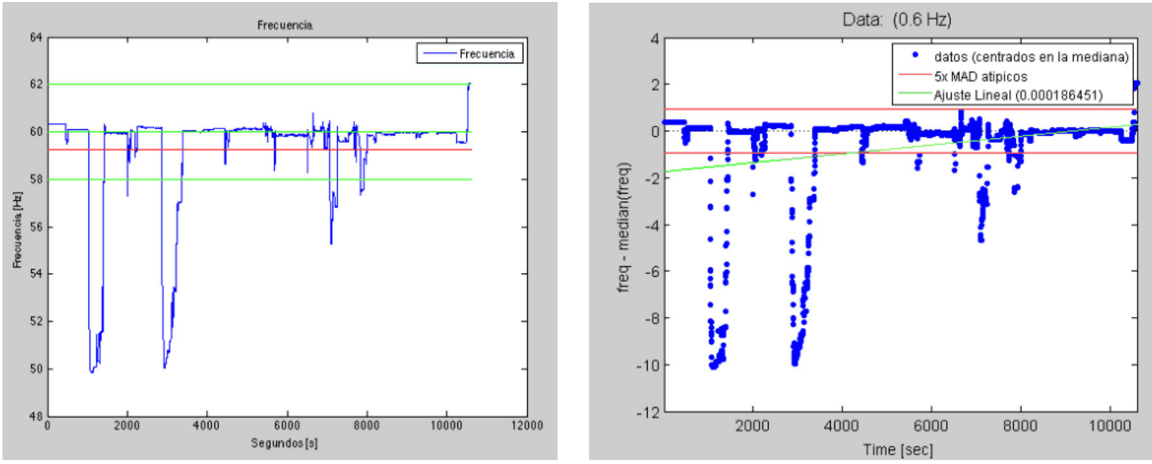
Figure 10. Engine acceleration and speed response of CUMMINS 6CTAA8.3-G1based power unit when working in bifuel mode

Generated power and cummulative energy during the test are described by the graphics in figure 11,*a*, while the behavior of frequency and frequency deviation are shown in 11,*b*. Important reductions in frequency response are observed when fuel and load are simultaneously changed, even for relatively small load steps. The power group did not experimented significant frequency changes at full load (DF < 2 Hz). There is a very slight fluctuation of output power irrespective of the load, which can be attributed to the engine governor stability.



a). Generated power and cummulative energy during the initial phase of the test

Figure 11.



b). Frequency and frequency deviation along the initial phase of the test

Figure 11 (cont.). Behavior of the power group frequency along the test

Engine Exhaust Emission Measurement

The emissions data, summarized in Table 7, show that operating the engines in bifuel mode results in an increase in CO when compared to diesel-only operation. Mansour et. al. [14] investigated the emissions and performance of a bifueled diesel engine and modeled the gas-diesel combustion reactions using chemical kinetic reaction mechanisms. They determined that the CO emissions increase when running in a bifuel mode was caused by non-optimized pilot timing, flame quenching, and partial burn. Engine manufacturers may be able to address these issues with designs tailored to specific fuel mixes, but little can be done to address these combustion properties in existing engines with aftermarket bifuel systems like GTI's.

Table 7. Engine specific exhaust emissions (emissions reduced to developed engine power) for the characteristic points of load cycle.

Fuel.	Power	CO2/POW	CO/ POW	O2/ POW	NOX/ POW	Exc. air
	[kW]	[g/kWh]	[g/kWh]	[g/kWh]	[g/kWh]	[%]
Diesel	44	988,30	11,54	2008,47	8,46	143
Diesel	89	773,86	5,69	955,38	6,42	84
Diesel	132	701,22	5,75	670,40	6,37	66
Diesel	179	676,44	5,38	502,30	5,89	51
Bifuel	89	1279,60	32,68	667,62	1,88	110
Bifuel	179	678,57	11,06	457,46	0,50	70

One solution to address the increase in CO and NMHC emissions is the use of oxidation catalysts which are commercially available and have been demonstrated to significantly reduce these emissions.

Results from the Bacharach analyzer showed high levels of unburned hydrocarbon in the exhaust gas when on bifuel.

According to the EPA regulations [20] (Appendix 2), the power group does not meet the emission regulations, particularly, the CO levels are above the limit values of 6,6. However, some authors attribute the CO increase to the insufficient Diesel injection calibration [17].

Engine Efficiency

The summary values of table 8 show the increasing efficiency of the generator set as the load increases. The dual fuel systems allow for LPG and Diesel to be consumed simultaneously with no decrease in performance.

The brake thermal efficiency was calculated by considering the calorific value and mass flow rate of both fuels:

Brake thermal efficiency = brake power/ ((mf x LHV)LPG + (mf x LHV)Diesel)

Table 8. Efficiency of the bifuel Cummins 6CTAA8.3-G1 power group for the defined values of loads fuel and air flow rates, in accordance to the particular load points of the test cycle.

Fuel	Power	Diesel	LPG	Air	"Mixture"	Energy	Eficiency
	[kW]	[kg/h]	[kg/h]	[kg/h]	[kg/h]	[kJ/h]	[%]
Diesel	44	19,36	0	682,015	701,37	887868,1142	17,84
Diesel	89	30,72	0	819,57	850,29	1409058,228	22,74
Diesel	132	40,57	0	976,58	1017,15	1861063,813	25,53
Diesel	179	52,36	0	1146,47	1198,83	2401856,21	26,83
Bi-Fuel	89	13,22	17,034	960,046	990,30	1409058,228	22,74
Bi-Fuel	179	32,93	18,92	1312,91	1364,76	2401856,21	26,83

$$x_c = \frac{m_{LPG}}{m_{LPG} + m_{Diesel}} \cdot 100 \ [\%]$$

The Diesel fuel with LPG substitute ratio x_c was defined as:

The limitation of the maximum pressure rate imposes the LPG substitute ratio x_c limitation. Also following the efficiency criteria and maximum gas pressure limitation criteria the LPG substitute ratio x_c= 20 - 30 is defined as optimal range values.

Power Correction Factor, Calculated in Accordance with ISO 3046 [5]

Since the power group was tested at atmospheric conditions very different from those corresponding to the standard values, the measured power must be corrected in accordance to the ISO 3046-1 standard: $P_x = \alpha \cdot P_r$.Corrected values of power and efficiency are those presented in table 9.

Table 9. Power and efficiency of the Bifuel Cummins 6CTAA8.3-G1 power group during the test cycle.

Fuel	Correction factor	Measured power	Corrected power	Measured efficiency	Corrected efficiency
	α	[kW]		[%]	
Diesel	0,7974	44	55,2	17,84	22,37
Diesel	0,7974	89	116,6	22,74	28,52
Diesel	0,7974	132	165,5	25,53	32,01
Diesel	0,7974	179	224,5	26,83	33,65
Bi-Fuel	0,8177	89	108,8	22,74	27,8
Bi-Fuel	0,8177	179	218,9	26,83	32,81

Conclusions

Engine testing was used to determine absolute performance, efficiency and emissions characteristics, to obtain comparisons between fuel systems, and to assess the possible inconveniences of using LPG from Cusiana. To achieve the technical goals, it was designed a test methodology based on a stepwise sequence of designated loads at cold/warm starting, idle, 25, 50, 75, and 100% of safety maximum load, for short time at generator set nominal speed.

The main conclusion drawn from the study is that Cusiana LPG is a viable alternative fuel for the CNG and Diesel engines. It was demonstrated that Diesel engines can operate in a bifuel mode with LPG at replacement rates around 40%. The efficiency is only one aspect of the power generation system operation. However, commercialization aspects such as cost/benefit analysis, reliability, durability, serviceability, and packaging across multiple applications must be considered.

As far as for the impact of LPG use on efficiency is concerned, no definite conclusions can be drawn from the work here presented because there was not any possibility to set a baseline for engine performance in every generator set, neither it was possible to optimize their power output for LPG fuel use.

Dual fuel engines give operators and service companies more flexibility in regards to supply, because they can use all forms of natural gas, LPG, and Diesel fuel simultaneously in the same engine. During the program two dual fuel generator sets were tested. These units were fitted with aftermarket conversion units and are running on LPG and Diesel, without any observable derating.

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Contact Information

Carlos Alberto Romero
cromero@utp.edu.co

ESEI disclaimer

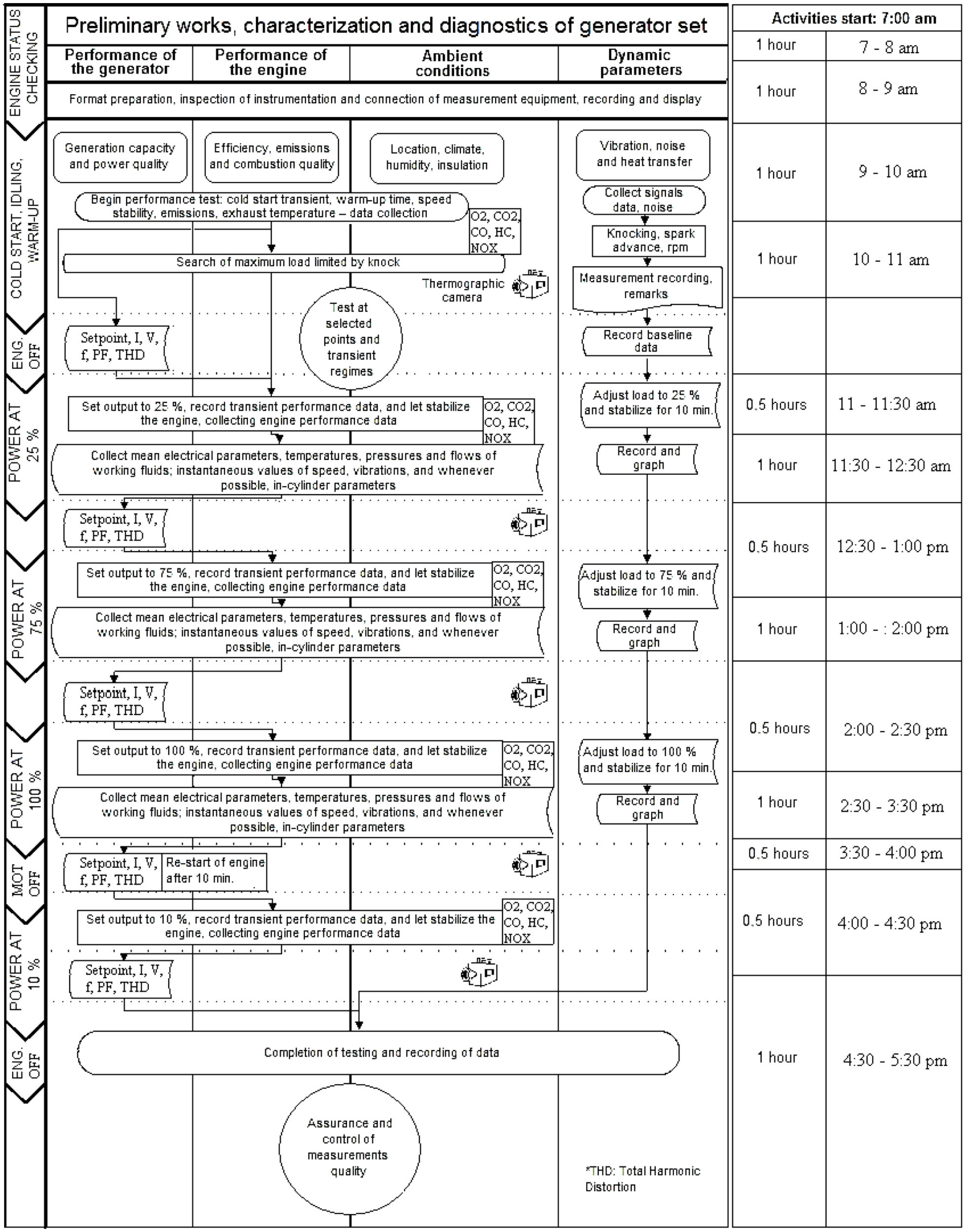
This demonstration project was supported both financially and operationally by ESEI S.A., at the request of ECOPETROL; however, any opinions, findings, conclusions, or recommendations expressly provided or implicit in this report are those of the author(s) and do not necessarily reflect the views of ESEI S.A. Reference in this report to any product, method, process, or service, or the use of any trade, firm, or corporation name is for the information and convenience of the public and does not constitute an endorsement, recommendation, or suggestion of any preference by ESEI S.A. or any of its employees.

Acknowledgments

This demonstration project evaluated the use of Cusiana LPG to power generator sets in oil wells, and was a collaborative effort involving industry and public support from a number of organizations. The project was initiated by ESEI S.A. with management and technical support from ESEI S.A., Universidad Nacional de Bogotá, and Universidad Tecnológica de Pereira. In addition to providing the LPG needed to conduct testing, Alsabana, as wells a R2 hosted the field demonstration and provided exceptional support from planning through project execution. The generator sets tested along the project were provided by Poilgas, Surperoil, Power Group, Ingenergía, R2 Energy, Cummins de los Andes. Bifuel systems used during the project were manufactured by Altronic and ComAp.

APPENDIX

Appendix 1. Flow chart of the field protocol designed for the test campaign



Appendix 2. Límit values of exhaust emissions for stationary units (EPA Tier 1-3 Nonroad Diesel Engine Emission Standards, g/kWh (g/bhp·hr))

U.S. EPA Non-Road and Stationary Emissions Regulations

<table>
<tr><th>kWm</th><th>(HP)</th><th>2004</th><th>2005</th><th>2006</th><th>2007</th><th>2008</th><th>2009</th><th>2010</th><th>2011</th><th>2012</th><th>2013</th><th>2014</th><th>2015</th><th>2016</th><th>2017</th></tr>
<tr><td>0 ≤ P < 8</td><td>(0 - 11)</td><td>Tier 1</td><td colspan="3">(7.5) / 8.0 / 0.80</td><td colspan="10" rowspan="2">(7.5) / 6.6 / 0.40</td></tr>
<tr><td>8 ≤ P < 19</td><td>(11 - 25)</td><td>Tier 1</td><td colspan="3">(7.5) / 6.6 / 0.80</td></tr>
<tr><td>19 ≤ P < 37</td><td>(25 - 50)</td><td colspan="4">(7.5) / 5.5 / 0.60</td><td colspan="5">(7.5) / 5.0 / 0.30</td><td colspan="5">(4.7) / 5.0 / 0.03</td></tr>
<tr><td>37 ≤ P < 56</td><td>(50 - 75)</td><td colspan="4" rowspan="2">(7.5) / 5.0 / 0.40</td><td colspan="5">(4.7) / 5.0 / 0.30 [EPA Option 1]</td><td colspan="5">(4.7) / 5.0 / 0.03</td></tr>
<tr><td>56 ≤ P < 75</td><td>(75 - 100)</td><td colspan="4">(4.7) / 5.0 / 0.40</td><td colspan="3" rowspan="2">3.3 / 0.19 / 5.0 / 0.02</td><td colspan="3" rowspan="2">0.40 / 0.19 / 5.0 / 0.02</td></tr>
<tr><td>75 ≤ P < 130</td><td>(100 - 174)</td><td colspan="3">(6.6) / 5.0 / 0.30</td><td colspan="5">(4.0) / 5.0 / 0.30</td></tr>
<tr><td>130 ≤ P < 225</td><td>(174 - 302)</td><td colspan="2">(6.6) / 3.5 / 0.20</td><td colspan="5">(4.0) / 3.5 / 0.20</td><td colspan="3" rowspan="3">2.0 / 0.19 / 3.5 / 0.02</td><td colspan="4" rowspan="3">0.40 / 0.19 / 3.5 / 0.02</td></tr>
<tr><td>225 ≤ P < 450</td><td>(302 - 603)</td><td>Tier 2</td><td colspan="6">(4.0) / 3.5 / 0.20</td></tr>
<tr><td>450 ≤ P < 560</td><td>(603 - 750)</td><td>Tier 2</td><td colspan="6">(4.0) / 3.5 / 0.20</td></tr>
<tr><td>560 ≤ P < 900</td><td>(750 - 1206)</td><td colspan="2">9.2 / 1.3 / 11.4 / 0.54</td><td colspan="5">(6.4) / 3.5 / 0.20</td><td colspan="4">3.5 / 0.40 / 3.5 / 0.10</td><td colspan="3" rowspan="2">0.67 / 0.19 / 3.5 / 0.03
3.5 / 0.19 / 3.5 / 0.04 (Non Generator)</td></tr>
<tr><td>> 900</td><td>(>1206)</td><td colspan="2">9.2 / 1.3 / 11.4 / 0.54</td><td colspan="5">(6.4) / 3.5 / 0.20</td><td colspan="4">0.67 / 0.40 / 3.5 / 0.10</td></tr>
</table>

TIER 1	TIER 2	TIER 3	TIER 4 (Interim)	TIER 4 (Final)

NO_x / HC / CO / PM (g/kW-hr)
(NO_x + HC) / CO / PM (g/kW-hr)
[Conversion: (g/kW-hr X 0.7457 = g/bhp-hr)]
Separate NO_x and HC standards separated by a forward slash.
Combined NO_x and HC standards enclosed by parentheses. "( )"

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ISSN 0148-7191

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