# Performance of a dual-fuel natural gas/ diesel engine in oil fields

## Comportamiento de un motor diesel de 1.105 hp operado mediante el sistema dual-fuel con diesel - gas natural en campos petroleros

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## Abstract

The dual–fuel system for diesel engines is described, which consists in substituting part of the fuel used by the internal combustion engine with natural gas or another gaseous fuel. This system allows significant savings in costs due to differences in the prices of diesel and natural gas, the on–site availability of gas, and the reduction in polluting gas emissions to the atmosphere attributable to the positive aspects of natural gas versus diesel fuel. The results of tests carried out on the dual–fuel engine are presented, and the best way to use this technology in the oil industry is indicated.

**Key words:** dual–fuel; natural gas/diesel engine; diesel saving; substituting diesel with natural gas.

## Introduction

The 1973 oil crisis, triggered by the oil embargo imposed by the Organization of the Petroleum Exporting Countries (OPEC) on countries that had supported Israel during the Yom Kippur war, including the United States and its Western European allies, not only led to a rise in the price of oil, but also had a strong inflationary effect and limited the economic activity of affected countries. There was a concomitant awareness of the importance of the rational use of oil resources, and various measures and mechanisms were designed to increase the efficiency of processes involving fossil fuels (Lafuente and Genatios, 2005).

The far-reaching effects of climate change worldwide in the last decades, attributed to greenhouse gas emissions (GGEs), have pushed researchers to study more efficient ways of using

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oil resources and design new technologies that reduce the amount of pollutants emitted into the atmosphere. One of the most well-known initiatives is the Kyoto Protocol by which signatory countries agreed to reduce GGEs to 1990 levels. For the period 2008–2012, the commitment is to reduce by at least 5% the emissions of the following six greenhouse gases that cause global warming: carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), and three fluorinated industrial gases. The Protocol also established mechanisms to encourage clean development programs (United Nations, 1998). In recent decades it has been necessary to establish more restrictive norms regarding the performance of certain thermal machines and the level of pollutants these are allowed to emit (US Environmental Protection Agency, 2012).

Colombia, for instance, has developed strategies for reducing polluting emissions, while also passing decrees and laws that regulate pertinent aspects. The government has encouraged the use of cogeneration systems and the application of emission-reducing technologies.

For refined fuels such as diesel, sulfur levels decreased from 5,000 ppm in 1990 to 500 ppm in 2009, with the nationwide goal being 50 ppm (Arango, 2009).

## Internal Combustion Engines and the Dual-Fuel System

An internal combustion engine (ICE) is a heat engine that transforms a fuel's chemical energy into mechanical energy in the shaft as the result of a combustion process within its chambers (Salazar, 2011). With the power produced in the shaft, either electricity is generated or pumps and/or compressors are put into movement. In addition, the residual energy released as heat can be used for cogeneration (Unidad de Planeación Minero Energético de Colombia, 2011),

The combustion process is an exothermic chemical reaction between a substance (called fuel) and an oxidant, usually atmospheric oxygen. Three elements are required to trigger the reaction: a fuel (material that burns), an oxidant (material that triggers burning), and a catalyst (that supplies the power required to reach combustion initiation temperature) (Karim, 1980). Combustion generates light, heat, and gases depending on the composition of the elements involved in the reaction, such as $CO_2$, $H_2O$ (as steam), soot, nitrogen oxides (NOx), carbon monoxide (CO), or others (Karim, 1980).

**ICEs have two methods of ignition:**

- Spark ignition, where the combustion of a homogeneous air-fuel mixture is ignited by a spark from a spark plug. Although commonly known as gasoline engines, other fuels are used in spark-ignition engines (SIEs) such as alcohol, other gaseous fuels, and/or mixtures.

- Compression ignition, where the heat generated from compression is enough to initiate the combustion process of the fuel as it is injected into the compressed air, forming a heterogeneous mixture in the combustion chamber (Payri, 2011). The fuel most commonly used in compression-ignition engines (CIEs) is pure diesel, but fractions of diesel oil can be injected into a compressed air-gaseous fuel mixture.

The ratio of energy obtained from the ICE shaft and that provided by the fuel is called brake efficiency or performance, and depends on the type of engine, cylinder dimensions, compression ratio, load, rotation speed, and other factors (Universidad Nacional de Colombia, 2009).

The ICEs, despite being machines with relatively low brake efficiency, have been the most used to generate power (Sanz, 2007). Table 1 shows the heat balance of ICEs for both diesel and gasoline engines.

**Table 1.** Heat balance of an internal combustion engine (ICE).

| Volumetric contraction | Type of motor | |
|---|---|---|
| | Diesel (%) | Gasoline (%) |
| Heat equivalent to effective work | 30 | 25 |
| Heat ceded to coolant | 30 | 30 |
| Heat in exhaust gases | 30 | 35 |
| Friction and radiation | 10 | 10 |

Source: Adapted from Sanz (2007).

Brake efficiency values up to 42% have been reported in ICEs and, although the power in the shaft remains relatively low as compared with that provided by the fuel, advantage is increasing being taken of the significant residual heat in cogeneration processes (Sanz, 2007).

The academia and manufacturers have studied the simultaneous use of diesel-gas in CIEs because of the decrease in operating costs attributable to the price difference between both fuels (Bedoya et al., 2007 and Pérez, 2011) as well as the potential reduction of emissions of NOx, particulate matter (PM), CO, and $CO_{2\,(}$Papagiannakis and Hountalas, 2004).

In CIEs of intermediate capacity that use diesel-gas simultaneously, compression ignition was maintained by the partial addition of diesel fuel, which forces diesel to be used as pilot fuel to ignite the gas (bi-fuel operation). These CIEs can be adjusted for bi-fuel or dual-fuel operation, alternating selective operation between bi-fuel or 100% diesel.

In the dual-fuel system, a standard diesel engine is attached to the equipment so that it can operate simultaneously with two types of fuel: a liquid fuel, which could be either diesel or biodiesel, and a gaseous fuel, which could be natural gas, liquefied petroleum gas (LPG), or biogas, among others.

The lower operational costs and the use of alternative fuel sources with dual-fuel engine operation have attracted many researchers to study the use of this technology in different areas. Initial experiments with the dual-fuel system were performed by Cave in 1929 and Helmore and Sökes in 1930 (cited by Liu, 1999), where hydrogen was introduced as secondary fuel in diesel engines. However, at that time the dual-fuel engine system was not used on a commercial level because of its mechanical complexity and the complications associated with relatively low compression ratios.

Dual-fuel systems have a broad range of applications in the car, marine, and power generation sectors, specifically in stationary engines, compressors, and pumps. Two technologies have been developed for dual-fuel operation in the specific case of its application in power systems, where control systems operate specifically to maintain the ICE rotation speed near a predefined reference value:

- HFO (high fuel operation): In this mode of operation, the ICE operates with a relatively high amount of diesel, with two modes of operation: (1) normal, in which the use of diesel fuel for engine operation is controlled; and (2) replacement, where part of the diesel is replaced by a fixed value of gas and the regulation of diesel in the combustion chamber continues. The main technical advantage of this system is that the engine is operated with diesel alone or diesel and gas in different proportions, granting significant flexibility to the equipment operator to operate the engine depending on the availability of gas or the amount of diesel the operator wants to save.

- LFO (low fuel operation). In this mode of operation, the required fuel is gas-controlled, and a small amount of diesel, which serves as pilot to trigger combustion in the chamber, is added. Figure 1 illustrates the dual-fuel system in both HFO and LFO modes.

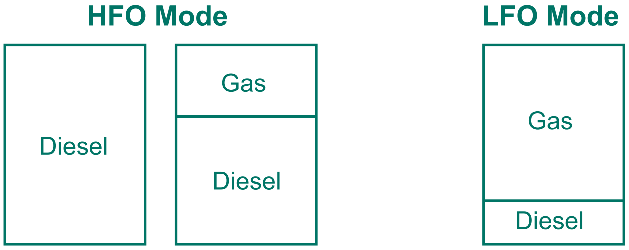

**Figura 1.** Dual-fuel system in HFO and LFO modes.

Figure 2 illustrates how the dual-fuel system operates in HFO mode. Pressure-regulated gas enters one end of the system while air enters the other end through the air filter. Both gases mix and pass on to the engine intake system. Important engine manufacturers such as Caterpillar, Man, Cummins, Deutz, Wartsila, and others, together with manufacturers of components such as Altronic, offer diesel engines equipped with a factory-installed dual-fuel system or endorse certain kits that can be purchased on the market that will not affect the engine's warranty if installed.

The system has the following characteristics:

- Installing the dual-fuel system does not compromise the performance of the original engine. A 1000 kW engine will maintain its level of power after the installation of the dual-fuel system, whether operated with 100% diesel or dual mode. There is no loss of engine power at the normal operating range of the system. A decrease in power will only occur in some cases, attributable to the composition of the gas; however, lost power can be recovered by decreasing

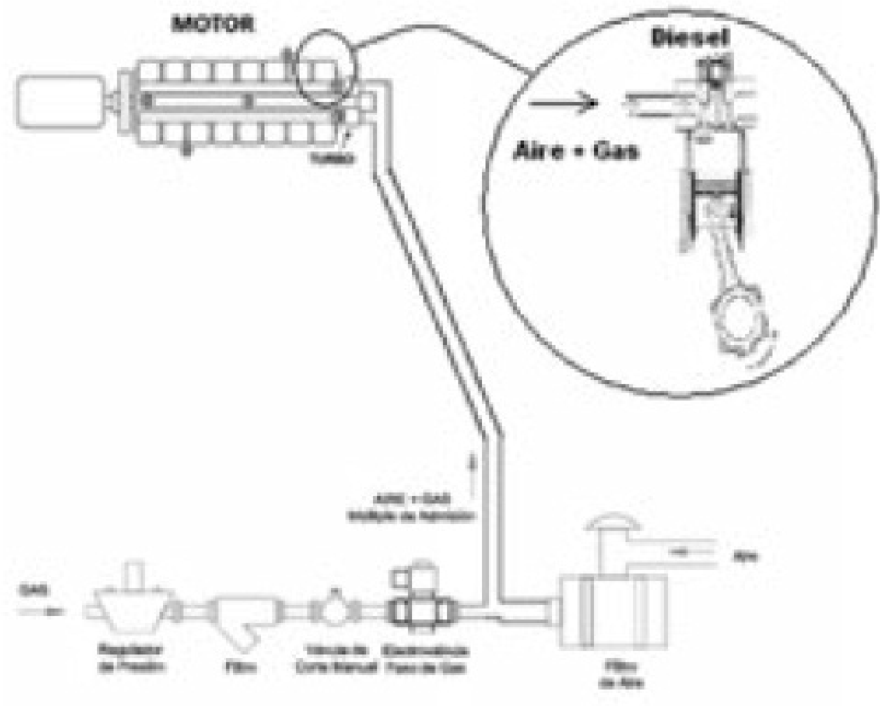

**Figura 2.** Flow chart of the dual-fuel system.

the amount of diesel replaced by gas (Sahoo *et al*., 2009).

- The engine has no drawbacks due to loss of stability or speed of response due to changes in load (Sahoo *et al*., 2009).

- The system is designed to smoothly switch from dual mode to diesel mode. The switch can be gradual or immediate (Sahoo et al., 2009).

- The parameters of heat due to radiation, efficiency, exhaust heat, and heat released into the cooling system remain virtually unchanged regarding the original values provided by the engine manufacturer. As a result, engines from diesel generating sets used in cogeneration applications recover the same amount of heat when operating in dual-fuel mode as when operating in 100% diesel mode (Poonia *et al*., 1999).

- Not only do polluting gases, such as NOx, decrease considerably (around 60%), but also particulate substances emanating from the exhaust port (also calculated around 60%) (Brachetti, 2010).

- Extensions in oil change intervals and service life of engines have been reported, mainly attributable to the clean combustion that characterizes natural gas (Pérez, 2011; Sahoo, 2009).

## How the dual-fuel system operates

The dual-fuel system is essentially a hybrid system that combines the characteristics of SIEs and CIEs. In an engine converted to dual operation, an air-gaseous fuel mixture is added to the combustion chamber, referred to as the primary fuel. A certain amount of diesel is then injected at the end of the compression stroke, referred to as the pilot fuel, which, because of the conditions of high pressure and temperature inside the cylinder, self-ignites and began the combustion process of the primary air-fuel mixture (Liu and Karim, 1977; Karim and Zhigang, 1992; Hountalas and Papagiannakis, 2000). Figure 2 shows how the air-gas mixture enters the combustion chamber and combustion occurs when diesel is supplied at the end of the compression stroke, causing the piston to move downwards and generating power.

In dual-fuel systems, the diesel replacement rate is defined as the amount of diesel replaced by gas (Z) as follows:

$$Z = \left(\frac{\dot{m}_{DI} - \dot{m}_{DD}}{\dot{m}_{DI}}\right) * 100 \qquad (1)$$

Z: level of replacement (%)
$m_{DI}$: massic consumption of diesel in diesel mode
$m_{DD}$: massic consumption of diesel in dual mode

In studies conducted on diesel engines operating simultaneously with gas, diesel substitution was substituted by up to 85% natural gas depending on the type of engine and its application (Bedoya et al., 2007; Papagiannakis and Hountalas, 2007). Above this level, problems occurred in the injectors as well as engine knocking, abnormal vibration, and high temperatures (Papagiannakis and Hountalas, 2007), but these will depend on the type of engine, fuel, engine load and operating site, among other factors. Therefore all equipment must be tested to determine the each unit's operating limits.

The dual-fuel diesel engine was unable to operate at 100% gas replacement because of the relatively high ignition temperature of natural gas (approximately 1300 °F). Because this temperature was not generated during diesel fuel compression in the engine cylinder, the natural gas could not be ignited. During the bi-fuel operation, diesel fuel had to serve as source of ignition of the air-gas mixture (Sahoo et al., 2009).

Research conducted by Altronic Inc., a supplier of dual-fuel kits, established that for each gallon of diesel #2 replaced in an engine, approximately 140 standard cubic feet (SCF) natural gas are required .

## Disadvantages of the dual-fuel system

Research indicates that problems may occur during the use of a dual-fuel system. These problems can include:

- Decreased system efficiency at low loads—the main problem of operating an engine in dual-fuel mode. In other words, the substitution level decreases as compared with other points of higher load of the engine so the system becomes more efficient (higher substitution of diesel with gas) as the engine's power requirement increases (Karim and Burn, 1980, Xiahua and Philip, 1986).

- Higher emissions of unburned hydrocarbons (HC) and CO when the engine operates at low load than when it operates with diesel alone (Karim and Burn, 1980; Xianhua and Philip, 1986).

- Problems in engine components when these enter into contact with gases, depending on the type of gas and its composition. Problems have mainly been reported with hydrogen sulfide ($H_2S$), which reduces the time between engine overhaul. Another problem reported was the presence of condensates in gaswell gas so a gas scrubber is desirable (Pérez, 2011).

In general, it is also recommended to operate the duel-fuel engine at a load higher than 50% nominal value; however, the engine can be operated at a lower load if the operator is not concerned about the amount of gas to be used or gas emissions. The engine should have a good gas filter and/or scrubber, depending on the gas's composition.

## Research on dual-fuel engines

Research has been conducted in which diesel or biodiesel (Kleinová *et al*., 2011) was mixed with gaseous fuels such as natural gas, biogas, LPG, hydrogen (Korakianitis *et al*., 2011), and acetylene (Lakshmanan and Nagarajan, 2011). Depending on the type of engine fuel used and its composition, different replacement rates of liquid fuel with gaseous fuel were obtained as well as different emission levels, which in most cases were lower than those of engines operating with diesel alone.

In India, Uma et al. (2004) studied a power generator set with a 50-kW (nominal value) diesel engine operating in dual-fuel mode with natural gas. Table 2 indicates both fuel and energy consumption at different loads.

**Table 2.** Fuel consumption and specific energy consumption at different loads.

| **Load (kW)** | **Fuel consumption** | | | | **Specific energy consumption** | |
|---|---|---|---|---|---|---|
| | Diesel mode | Dual-fuel mode | | Diesel replacement rate (%) | Diesel mode (MJ/kWh) | Dual-fuel mode (MJ/kWh) |
| | Diesel (kg/h) | Diesel (kg/h) | Natural gas (Nm³/h) | | | |
| 10 | 5.3 | 1.9 | 57 | 64 | | 34 |
| 20 | 7.2 | 1.3 | 66 | 82 | | 18 |
| 30 | 9.8 | 1.5 | 81 | 85 | 14 | 15 |
| 40 | | 3.7 | 112 | 70 | | 16 |

Source: Uma *et al.* (2004).

Equation (1) indicates a maximum replacement of 85% diesel with gas at a 30-kW load, which corresponds to 60% of the engine's nominal load; however, it was possible to operate the engine at a 40 kW-load, which corresponds to 80% nominal load with a 70% replacement rate of diesel.

Specific energy consumption was also observed to increase with decreasing engine load. Therefore it is recommended to always operate engines at their nominal load. Furthermore, higher specific energy consumption was observed with the dual-fuel system, possibly attributable to the calorific value of the gas and flame speed (Uma et al., 2004; Parikh, 1989;. Sridhar *et al*., 2001). Finally, CO, $CO_2$, and $CH_4$ increased and NOx and PM decreased in the dual operation mode as compared with diesel operation alone (Table 3).

**Table 3.** Emission potential at different loads.

| Parameter | Load (kW) | | | | | |
|---|---|---|---|---|---|---|
| | 10 | | 20 | | 30 | |
| | Diesel | Dual-fuel | Diesel | Dual-fuel | Diesel | Dual-fuel |
| CO (ppm) | 181 | 635 | 207 | 640 | 284 | 734 |
| $CO_2$ (%) | 3.1 | 6.2 | 4.2 | 7.1 | 5.7 | 9.2 |
| HC (ppm) | 109 | 119 | 132 | 141 | 180 | 182 |
| $CH_4$ (ppm) | 7 | 18 | 8.4 | 24 | 10.2 | 21 |
| $SO_2$ (ppm) | 4.6 | 1.1 | 5.4 | 1.2 | 6.8 | 1.5 |
| NOx (ppm) | 172 | 93 | 230 | 140 | 279 | 170 |
| PM (mg/$m^3$) | 22 | 18 | 26 | 24 | 29 | 24 |

Source: Uma *et al*. (2004).

Studies conducted by the Technical University of Kaiserslautem, published in SBS, Bosch and Clean Air Power, show that the potential for reducing emissions in a diesel engine where 50% of the diesel fuel has been replaced with natural gas is as follows: CO, 95%; HC, 66%; PM, 42%; and NOx, 35%.

These results agree with those obtained by Bedoya (2007 and Papagiannaki (2007), but contradict those obtained by Uma et al. (2004). Therefore, emission reduction seems to depend on factors such as type of gas, type of engine, and load, with each experiment yielding results specific to the type of experiment.

By using natural gas, gas emissions into the atmosphere decreased, depending on the type of gaseous fuel. When biogas was used as primary fuel, the emissions of certain pollutants, such as CO, unburned or total hydrocarbons (THC) and $CH_4$, increased (Bedoya, 2007; Silva *et al*., 2012).

The chemical composition of biogas makes it a relatively poor fuel because it contains an substantial amount of $CO_2$ and pollutants, such as siloxane materials, as well as moisture and $H_2S$, making it necessary to submit the biogas to at least one pre-treatment of cleaning and drying and a very careful selection of the engine (Silva et al., 2012).

## Applying dual-fuel systems in oil fields

Diesel fuel consumption in production facilities using this fuel in ICEs has a significant effect on operational costs because of the price of the fuel as well as transportation and storage costs.

The way production facilities handle diesel fuel is not the most adequate, which together with transportation difficulties often due to the geographical location of the facilities, affects the availability of clean fuel and sometimes results in the shortage of clean fuel, which, in turn, can hinder or limit HC production.

The implementation of the dual-fuel system in diesel engines allowed savings in operational costs attributable to the difference in price between diesel and natural gas, the availability of gas, and the decrease in GGEs into the atmosphere because of the favorable characteristics of natural gas as compared with those of diesel fuel. The dual-fuel technology has allowed oil companies to take advantage of the natural gas generated in flaring for use in engines in production facilities, which translates into savings in logistics and fuel storage costs, mainly in oil fields with little natural gas production or during production testing phases.

The optimal implementation of the dual-fuel system depended on several factors, including engine type, use given to the engine, type of gas used, and operating conditions. This comprehensive study was able to identify aspects relevant to the correct implementation and testing of the system and thus ensure its best performance, reaping the greatest benefits for the company taking into account the investment made and the benefits obtained by applying this technology. Figure 3 illustrates a typical installation of a dual-fuel system in a diesel generator:

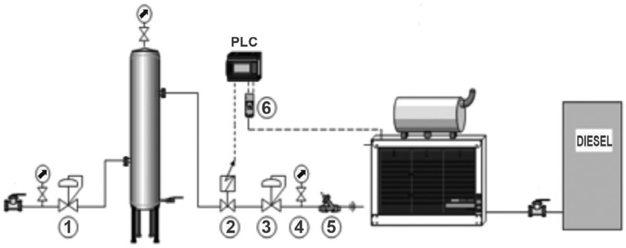

**Figure 3.** Flow chart of the dual-fuel system using gaswell gas and a scrubber in a diesel engine.

The system can be implemented in the HC sector in pumping systems, compressors, pumps, and power generation. When gaswell gas is used, it is always recommendable to have gas filters and scrubbers installed so that the gas entering the engine is of the highest quality possible.

The costs of implementing the dual-fuel system are low if the savings obtained are taken into account. Price increases depending on any additional measurement, control, or security components installed in the facility; however, basic installation kits can be purchased in the market starting at around US$3000. However, it is always recommended to seek good technical advice so the product selected is the one that best adapts to the energy available and the needs of each company.

## Setting up the Tests

A series of tests were designed to evaluate the mechanical and environmental performance of a diesel power generator set using the dual-fuel system. Different levels of replacement and engine loads were used to determine what actions need to be taken to improve the replacement level for the test equiment.

## Test equipment

The characteristics of the equipment used (Figure 4) are as follows: Caterpillar C27Genset power generator set; Caterpillar C27 engine; 4 strokes; 12 cylinders; speed, 1800 rpm; 1105 hp; turbo-charged; injection time, 25-45 BTDC; voltage, 480 volts; power, 906 kVA/725 KW; and power factor, 0.8.

Figure 5 shows how the tests were set up and the components used.

**Figure 4.** Power generator set used.

## Description of natural gas and diesel used in the tests

Table 4 presents the characteristics of the diesel fuel used in Colombia.

**Table 4.** Characteristics of diesel fuel in Colombia.

| Characteristics | Units | Method | Value | 640 | 284 | 734 |
|---|---|---|---|---|---|---|
| Cetane index | | ASTM D-4737 | 56–58 | 7.1 | 5.7 | 9.2 |
| Viscosity at 40 °C | 109 | 119 | 132 | 141 | 180 | 182 |
| | mm²/s | ASTM D-445 | 1.9 | 24 | 10.2 | 21 |
| Lubricity | microm-eters | ASTM D-6079 | | 1.2 | 6.8 | 1.5 |
| Sulfur | ppm | | 30–50 | 140 | 279 | 170 |
| Density | kg/m³ | | 825–835 | 24 | 29 | 24 |
| American Petroleum Institute (API) gravity | | | 38–40 | | | |

Source: Instituto Colombiano de Petróleo (XXXX).

Table 5 indicates the chromatography of the gaswell gas used in the tests, under sampling conditions of 20.0 psig at 87.0 °F.

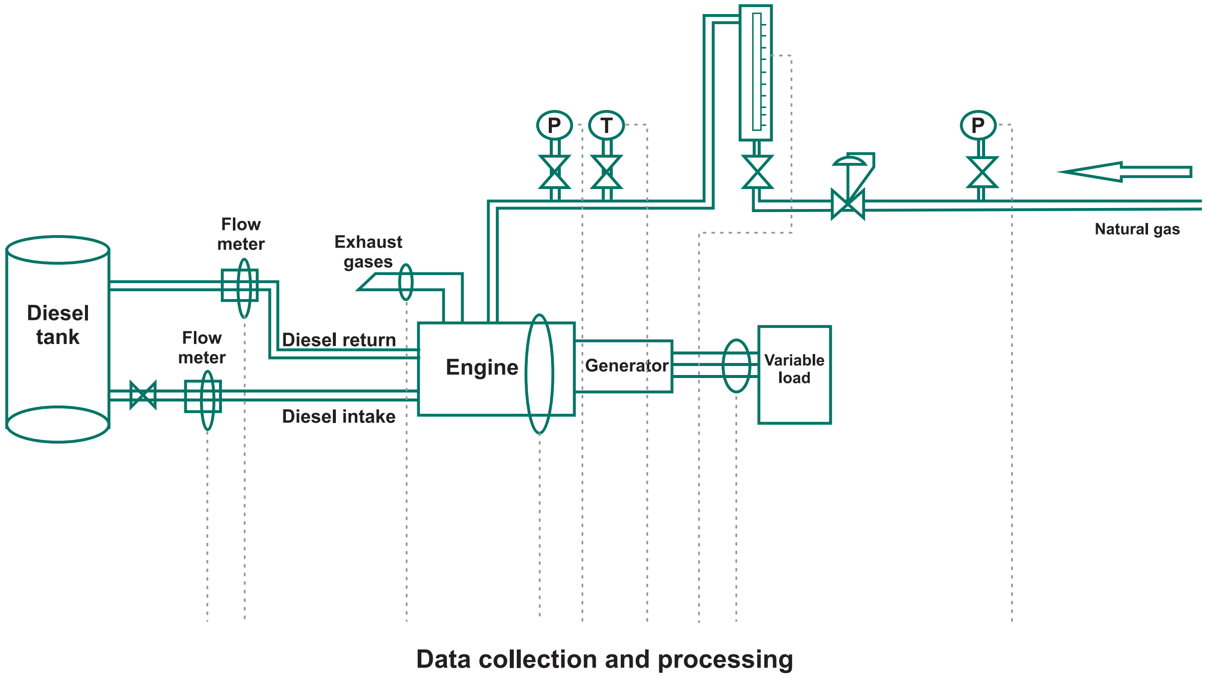

**Figure 5.** Flow chart of trial set-up and instrumentation.

**Table 5.** Gas composition report.

| Component | | Molar % | Weight (%) |
|---|---|---|---|
| $H_2$ | Hydrogen | 0.00 | 0.00 |
| $H_2S$ | Hydrogen sulfide | 0.00 | 0.00 |
| $CO_2$ | Carbon dioxide | 5.18 | 10.06 |
| $N_2$ | Nitrogen | 0.59 | 0.73 |
| $C_1$ | Methane | 73.47 | 52.05 |
| $C_2$ | Ethane | 10.93 | 14.51 |
| $C_3$ | Propane | 6.20 | 12.06 |
| $iC_4$ | i-butane | 0.97 | 2.49 |
| $nC_4$ | n-butane | 1.49 | 3.81 |
| $iC_5$ | i-pentane | 0.29 | 0.93 |
| $nC_5$ | n-pentane | 0.27 | 0.85 |
| $C_6$ | Hexanes | 0.29 | 1.09 |
| $C_7$ | Heptanes | 0.18 | 0.70 |
| $C_8$ | Octanes | 0.11 | 0.50 |
| $C_9$ | Nonanes | 0.02 | 0.15 |
| C10 | Decanes | 0.01 | 0.05 |
| C11 | Undecanes | 0.00 | 0.02 |
| | Total calculated gas properties | 100.00 | 100.00 |
| | Specific gravities of gas | 0.7832 | (Air=1@ 14.73 psia, 60 °F |
| | Real calorific power | 1227.6 | BTU.ft$^3$ @ 14.65 psia, 60 °F |
| | Net calorific power | 1114.1 | BTU.ft$^3$ @ 14.65 psia, 60 °F |

Source: Core Laboratories Colombia (XXXX).

## Measuring the electrical charge

An AEMC 3945-B power quality analyzer was used to measure the power delivered by the device (Table 6).

**Table 6.** Technical data of the AEMC 3945-B analyzer.

| Specifications | Range | Resolution | Precision |
|---|---|---|---|
| Voltage | 15–480 V | 0.1 V | 0.05% ± 2 cts |
| Frequency | 40–69 Hz | 0.01 Hz | **± *0***.01 Hz |
| Current | 0–1200 A | 0.1  A | **± *(0***.5% + 2 cts) |
| Active power | 0–9999 kW | 4 digits | **± *1%*** |
| Reactive power | 0–9999 kVAR | 4 digits | **± *1%*** |
| Apparent power | 0–9999 kVA | 4 digits | **± *1%*** |
| Power factor | -1.00 to 1.00 | 0.001 | **± *1***.5% |
| Active energy | 0–9999 mWh | 4 digits | **± *1%*** |

## Measuring engine exhaust gases

Engine exhaust gases were measured using an E Instruments E4400-C combustion gas and emissions analyzer, whose characteristics are presented in Table 7.

**Table 7.** Technical characteristics of the E4400-C combustion gas and emissions analyzer.

| Parameter | Sensor | Range | Resolution | Precision |
|---|---|---|---|---|
| $O_2$ | Electrochemical | 0–25% | 0.1% | 0.2% vol |
| CO | Electrochemical | 0–8000 ppm | 1 ppm | 10 ppm |
| $CO_2$ | Calculated | 0–99.9% | 0.1% | |
| NO | Electrochemical | 0–5000 ppm | 1 ppm | 5 ppm |
| NOx | Calculated | 0–5000 ppm | 1 ppm | |
| CxHy | Pellistor | 0–5% | 0.01% | 5% |
| Excess air | Calculated | 0–850% | 1 | |
| Efficiency | Calculated | 0–100% | 0.1% | |
| Temperature | Tc K | -20 to 1250 °C | 0.1 °C | |

## Measuring diesel fuel consumption

A GW TM-10 meter was used to measure diesel fuel flow, volume, and time. The meter was installed in the engine supply and return lines. See Table 8 for technical characteristics of the meter.

**Table 8.** Technical characteristics of the GW TM-10 flow meter.

| Technical characteristic | Range |
|---|---|
| Maximum service pressure | 300 psi |
| Precision | 1.50% |
| Flow range | 18.9 to 190 L/min |
| Temperature range | -40 °C to +121 °C |

## Measuring pressure and temperature

Pressure was measured using a WIKA 233-334 manometer, last calibrated in July 2013 (see Table 9 for technical characteristics of the manometer), and temperature was measured using a WIKA A50 thermometer, also last calibrated in July 2013 (see Table 10 for technical characteristics of thermometer).

**Table 9.** Technical characteristics of the WIKA 233-34 manometer.

| Characteristic | Value |
|---|---|
| Maximum service pressure | 10 psi |
| Precision | 0.50% |
| Pressure range | -20 °C to 65 °C |

**Table 10.** Technical characteristics of the WIKA A50 thermometer.

| Characteristic | Value |
|---|---|
| Maximum temperature service | 75 °C |
| Precision | Class 2 |
| Temperature range | -20 °C to 60 °C |

## Measuring the flow rate of natural gas

Natural gas flow rate was measured with a WIKA LZB-4 rotameter, last calibrated in July 2013. See Table 11  for technical characteristics.

**Table 11.** Technical characteristics of the WIKA LZB-4 rotameter.

| Characteristic | Value |
|---|---|
| Maximum pressure service | 100 psi |
| Precision | 0.5% |
| Range | 100–500 $ft^3/h$<br>500–1.000 $ft^3/h$<br>1.000–5.000 $ft^3/h$ |

## Results

The engine was tested using a variable electrical load. A series of variable resistors were used achieve the load levels required by the engine. Data recorded for the different levels of replacement obtained by changing incoming gas pressure to dual-fuel mode are given in Tables 12 and 13. Figure 6 illustrates the data recorded by the diesel fuel consumption analyzer.

**Table 12.** Record of fuel consumption.

| % Load (kW) | Fuel consumption | | | | |
|---|---|---|---|---|---|
| | Diesel mode | Dual-fuel mode | | | Replacement rate of diesel (%) |
| | | | Natural gas | | |
| | Diesel (gal/h) | Diesel (gal/h) | $ft^3$/ha | Pressure (psi) | |
| 25% | 11.9 | 10.5 | 221 | 1 | 11.8 |
| | | 10.4 | 236 | 2 | 12.6 |
| | | 10.2 | 268 | 3 | 14.3 |
| | | 10.1 | 284 | 4 | 15.1 |
| | | 9.5 | 378 | 5 | 20.2 |
| | | 9.8 | 331 | 6 | 17.6 |
| 50% | 21.8 | 19.1 | 454 | 1 | 12.4 |
| | | 18.9 | 488 | 2 | 13.3 |
| | | 18.5 | 555 | 3 | 15.1 |
| | | 18 | 639 | 4 | 17.4 |
| | | 17.2 | 774 | 5 | 21.1 |
| | | 17.4 | 740 | 6 | 20.2 |
| 75% | 34.1 | 30.2 | 593 | 1 | 11.4 |
| | | 29.9 | 639 | 2 | 12.3 |
| | | 29.1 | 761 | 3 | 14.7 |
| | | 28.7 | 821 | 4 | 15.8 |
| | | 28.3 | 882 | 5 | 17.0 |
| | | 27 | 1080 | 6 | 20.8 |
| 100% | 49.7 | 43.8 | 821 | 1 | 11.9 |
| | | 43.3 | 891 | 2 | 12.9 |
| | | 42.3 | 1030 | 3 | 14.9 |
| | | 41.8 | 1099 | 4 | 15.9 |
| | | 40.9 | 1225 | 5 | 17.7 |
| | | 39.2 | 1461 | 6 | 21.1 |

**Table 13.** Data registered by the combustion gas analyzer.

| Parameter | Engine load | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 25% | | 50% | | 75% | | 100% | |
| | Diesel | Dual | Diesel | Dual | Diesel | Dual | Diesel | Dual |
| CO (ppm) | 227 | 520 | 255 | 601 | 272 | 670 | 298 | 699 |
| $CO_2$ (%) | 3.9 | 6.1 | 4.3 | 7.9 | 5 | 8.9 | 5.6 | 9.4 |
| NOx (ppm) | 250 | 120 | 310 | 135 | 390 | 167 | 402 | 198 |
| HC (ppm) | 120 | 129 | 145 | 165 | 181 | 189 | 192 | 193 |

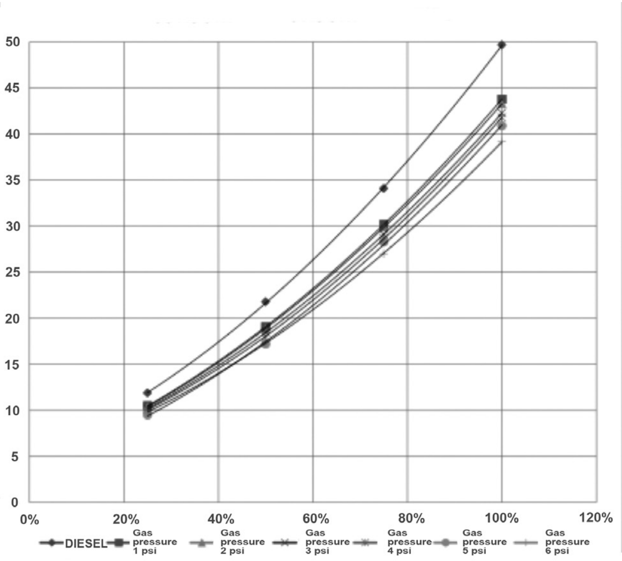

**Figure 6.** Diesel fuel consumption data recorded by analyzer.

Figure 6 shows how diesel replacement levels improve with increasing loads.

## Conclusions

The dual-fuel system is a useful tool to use in diesel engines when gas is available and, in most cases, can translate into significant cost savings and reduced emissions.

The results obtained when testing the diesel generator set were below the replacement levels obtained by researchers in laboratory conditions. Maximum replacement rate was 21% whereas Uma et al. (2004), for example, reported up to 85% replacement of diesel with natural gas.

The maximum replacement level changed at low and high engine load. To achieve better replacement rates, it was necessary to increase incoming gas pressure.

Emission measurements obtained in this study were similar to those of Uma et al. (2004), with NOx decreasing and CO and $CO_2$ increasing with dual-mode operation. Other studies, however, have yielded different results, which can be attributed to the composition of the natural gas used in each experiment as well as the conditions of the equipment used and other variables.

Future research should address the compression ratio and injection timing to improve the replacement rate and thus achieve levels gotten by other researchers, which could be feasible by adjusting the engine setting.

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