EXHAUST EMISSIONS CHARACTERISTICS: AN EXPERIMENTAL STUDY ON DIESEL ENGINE OPERATED WITH MIXTURES OF DIESEL AND NATURAL GAS


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Abstract. The objective of this research is to study the emission characteristics of a commercial diesel engine working with natural gas and diesel. The electrical-mechanical system is composed of a 8.3-L Cummins 6CTA turbo charger diesel-engine with mechanical power of 188 kW at 1800 rpm, coupled with an Onan Genset generator of 150 kW. An Alpha Ohmic charge bank was used to evaluate the engine performance. The exhaust gases were monitored with a KM 9106 gas analyzer made by Kane International Limited. The diesel-engine system is equipped with an electric charge bank, pressure and temperature sensors, gas, air and diesel flow meters, a gas analysis probe and a data acquisition system. Emissions of CO₂, CO, NO₂, NO and CₓHᵧ were measured at different loads. It was verified that CO₂, CO and NOₓ (NO+NO₂) emissions increase in dual fuel operation at all loads as compared to the values obtained with pure diesel operation. The emission concentrations in dual fuel and diesel modes are compared with the values reported in the literature.

Keywords: dual engine; exhaust emissions; internal combustion engines

1. INTRODUCTION

A shortage of crude oil will be expected during the early decades of this century. In addition, air pollution is becoming more serious and more strict regulations of both local and global emissions from engine are anticipated.

The use of alternative gaseous fuel in diesel engine is increasing worldwide. The applications of diesel engines employing gaseous fuels for power generation, in a so-called dual mode operation, range from on-site power generation to powering public transportation vehicles. The use of gaseous fuels is prompted by the cleaner nature of their combustion compared to conventional liquid fuels as well as their relatively increased availability at more attractive prices. This is also motivated by lower maintenance costs and longer engine life, following developments in cryogenic technology to economically store and transport the fuel in liquefied form. Natural gas satisfies the previous requirements as a result of its worldwide usage. Moreover, it mixes uniformly with the air, resulting in efficient combustion and substantial reduction of emissions in the exhaust gas (Papagiannakis and Hountalas, 2003).

Natural gas combustion is characterized by a long ignition time delay and cannot be used directly as a fuel for an internal combustion diesel engine. Therefore, some type of ignition aid is required (Mbarawa et al., 2001).

In dual-fuel engines, a carburetted mixture of air and high octane index gaseous fuel (natural gas) is compressed and then fired with a liquid fuel injection which ignites spontaneously at the end of compression phase, using the difference of flammability of the two
fuels. The presence of the gaseous fuel influences both pre-ignition and post-ignition processes in a complex manner, depending mainly on the fuel used, its concentration and operating conditions (Karin, 1980). Many researches on this topic have been reported in the literature (Reitz and Rutland, 1995; Bi and Agrawal, 1998; Mansour et al., 2001; Mbarawa et al., 2001; Papagiannakis and Hountalas, 2003; Lee et al., 2003; Uma et al., 2004; Shet and Salaray, 2004; Payri and Guardiola, 2005; Costa, 2007).

Experimental investigations to measure the performance and emissions of a diesel engine are complex, time-consuming and costly. Diesel exhaust emissions influence air pollution significantly. In particular, NOₓ, smoke and SO₂ emissions have damaging effects upon the environment and people. Therefore, with regard to the internal-combustion engine, decreasing the level of exhaust gas emissions is always considered as an important target to be achieved.

The objective of this experimental work is to examine the level of exhaust emissions of a dual-fuel diesel engine, operating with natural gas and diesel.

### 2. EXPERIMENTAL METHODOLOGY

#### 2.1. Description of natural gas and diesel fuel compositions

The main properties of the natural gas and liquid diesel fuel used in the present experimental investigation are given in Table 1. These values are representative of typical commercial fuels supplied in Campina Grande City, Paraiba State, Brazil. Methane is the main constituent of natural gas, resulting in a relatively high octane number, which renders it suitable for high compression rate engines.

#### 2.2. Experimental apparatus and procedures

##### 2.2.1. System description

**a) The electromechanical system**

The electromechanical system is composed of a 8.3L CUMMINS 6CTA turbo charger diesel-engine with mechanical power of 188 kW at 1800 rpm, coupled with an Onan Genset generator of 150 kW. The unit is well equipped with air, gas and diesel flow meters, temperature and pressure sensors in several points of the system and probes for analysis of gases. All data are collected in real time with an appropriate data acquisition system. Figure 1 presents the electromechanical system composed of the diesel engine with six cylinders in line, with 188 kW, coupled with the electric generator.

**b) The data acquisition system**

The data acquisition system is composed of reading and signal treatment units, and a Pentium 4 personal computer which processes and stores all information collected in real time. Figures 2 and 3 illustrate the graphical interface of the acquisition system developed in MATLAB environment and the data acquisition system, respectively.

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**Table 1. Basic composition of diesel and gaseous fuels used.**

<table>
<thead>
<tr>
<th>Fuel (source)</th>
<th>C₁₂H₂₆</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel (Medeiros et al., 2002)</td>
<td>98.53%</td>
<td>1.47%</td>
</tr>
<tr>
<td>Natural Gas (PBGAS, 2006)</td>
<td>89.42%</td>
<td>7.24%</td>
</tr>
</tbody>
</table>

![Figure 1. Diesel-engine electrical generator system.](image-url)
c) System for power measurement in the engine generator

To provide mechanical power to the engine, the electric power system is configured in the generator, through an ALPHA OHMIC bank of resistive load, with capacity of 150 kW. Figure 4 displays the load bank installed and linked to the generating unit.

d) The gas analysis system

To evaluate the pollutant emission levels of the diesel engine operated in the previously established conditions, an analyzer of gases manufactured by Kane International Limited, model KM 9106, was used. Figures 5, 6 and 7 show the combustion gases analysis unit, the programming and control unit, and the installation of the probe to obtain gas samples, respectively.

2.2.2. Experimental procedure

The dual fuel mode uses compressed natural gas as the primary fuel and quantities of diesel pilot fuel for ignition. The engine is also equipped with a dual-fuel conversion kit (Figure 8). The kit engine operates on either 100% diesel fuel or in a dual-fuel mode.

Natural gas is introduced into the intake air system, in such a way not to modify the original characteristics of the diesel engine.

Assays have been performed at several electrical power levels in the electrical load bank, at the speed of 1800 rpm and diesel replacement rates starting at 82.28% at 11.8 kW up to 88.4% at 110 kW, and then decreasing to 83.50% at 130 kW. A pilot experiment was first conducted to determine parameters such as duration of experiment, gas flow rate, and air and diesel contents for each load. During the pilot test the engine was initialized and, after 15 minutes, the emissions were measured. This initial period of time allows the engine to stabilize. Other details
about the experimental apparatus and procedures can be found in Costa (2007).

3. RESULTS AND DISCUSSIONS

3.1. Analysis of the pollutant emission

Results of emissions measurement for the engine in single diesel mode and dual fuel mode are presented and a brief discussion on the results is given, when the engine operate in dual mode with substitution rate changing to the 78.7% at 84.5% of natural gas.

Figure 9 depicts the behavior of the emissions concentration of carbon monoxide for several conditions of load of the engine and diesel replacement rates. For the engine operating with 100% diesel, it can be observed that a decrease of CO emissions is effected with increasing power, which is expected in the case of diesel-cycle engines, since this engine is a weak CO producer. CO emissions increase with natural gas fueling, according to Mansour et al. (2001).

In dual mode, with increasing load on the engine, there is a sharp increase in the percentage of CO, which reaches a maximum value of 0.2055%, when the engine operate with 84.5% of natural gas at a load of 50 kW, after which the emission rates start to decrease, given a sign of deterioration of the combustion reaction at higher loads.

At lower loads the quantity of fuel supplied was small, i.e., the mixture remained lean, which produced less heat in the chamber resulting in lower flame temperature and consequently lower conversions of CO to CO$_2$.

High concentration of CO in the dual fuel exhaust is an indication of incomplete combustion, and could be due to combination of factors such as low heating value of gas, low adiabatic flame temperatures, and low mean effective pressures. Additionally, the engines are not actually designed to operate with gas, but with diesel.

Emissions of pollutant depend on the quality of the fuel, the fuel consumption and the type of engine in study. Fuel consumption varies under different load conditions. Besides, with the same load and under different operation conditions (pure diesel and in dual mode), the specific consumption varies. Therefore, to compare pollutant emissions is a difficult task. However, some results obtained may be compared with results supplied in the literature. All results have been obtained in stable operation (non-knocking) conditions. The
exhaust gas temperature changes from 248°C to 435°C.

Shenghua et al. (2003), testing a WD 615-64 super feed diesel engine, with maximum power of 164 kW at 2200 rpm and specific consumption of 228 g/kWh, have reported that the CO emissions of the engine operating at 1000 rpm increased when the methane concentration (gas) was higher, reaching values of approximately 0.2%, for a percentage of gas equal to 84%.

Henham and Makkar (1998), testing a 2-cylinder, four-cycle Lister Peler LPWS2 engine, with indirect injection, have reported CO concentrations of approximately 0.35% for a mixture with 55% of methane and 45% of diesel, and 0.04% for the case of pure diesel, at 2000 rpm and a torque of 40 Nm.

Figure 10 shows the effect of load on the emissions of carbon dioxide (natural gas 84.5% and pure diesel 15.5%). It can be observed that the level of emission of CO₂ increases with increasing load. This parameter provides some information on the quality of the combustion, indicating higher efficiency for the highest level of this component and a decrease in the level of CO emissions. Higher percentages of CO₂ in the exhaust gas suggest higher fuel oxidation rates at constant engine speed, more release of heat for power conversion and enhanced combustion as more CO is converted to CO₂.

Mansour et al. (2001) report concentrations of CO₂ ≈ 4.5% at 1800 rpm and 140 kW for unknown substitution rates. These values show good agreement with the results obtained in this work (approximately 6.0% for rate substitution of 82% in Figure 10).

Figure 11 shows the effect of load in the emissions of nitrogen oxides. For the situation of the engine operating with pure diesel (Figure 11), a big increase in the NO emission is
observed at loads up to 100 kW and, starting from this point, the curve gives an indication of stabilization of emissions concentrations. The formation of oxides of nitrogen is generally favored by the increased oxygen concentration at higher temperatures. Therefore, at lean fuel-air ratios, when oxygen is available in abundance, the effect of temperature is expected to predominate. A slight decrease in the combustion temperature is thus expected with lean dual fuel operation, since the delay period is extended and more into the expansion stroke (Karim, 1980).

Papagiannakis and Hountalas (2003), using a four-cycle diesel engine, working at a speed from 1000 to 3000 rpm, and with varied loads (40%, 60%, and 80% of the full engine load) reported that the percentage of NO for a condition of 2000 rpm, using 80% of engine load and also diesel substitution rate of 80%, is equal to 0.05%. Mansour et al. (2001), for a condition of 1800 rpm and 140 kW, report a NOx (NO + NO2) concentration of approximately 0.05%, for an unknown substitution rate.

Figures 12 and 13 illustrate the effect of load in the emissions of nitrogen oxides and NOx, respectively. For load values of up to 100 kW, the emission levels are in agreement with CONAMA 315/2002 (Brazil legislation), for the conditions of pure diesel (5.0 g/kWh). Increase in NOx emission levels with increasing load was observed because NOx emissions are very dependent on the combustion chamber temperature. According to Sethi and Salariya (2004), at higher chamber temperature the reaction N2 + O2 → 2 NO takes place. Temperature drops quickly during expansion and exhaust strokes, but the reverse reaction or dissociation of NO is not rapid enough to establish equilibrium and therefore higher amounts of NOx appear in the exhaust gases at higher loads.

According to Shenghua et al. (2003), at 1000 rpm and methane concentration (gas) of 84%, the concentration of NOx was approximately 220 ppm, increasing with diesel concentration in the mixture. Furthermore, these authors report that the NOx emissions in both operation manners (pure diesel and dual mode), increase with increasing load. They also state that, if the engine is not very well adjusted, discharges of emissions (approximately 1500 ppm) are found, which is caused by soft detonation.

According to Karim (1980), a low decrease in NOx concentration is expected for low fuel-air ratio. With further enriching of the gas-air ratio, NOx concentration increases with decreasing rates compared to diesel operation, until the effective flammability limit is reached.
At high loads, NO\textsubscript{x} concentrations may even well exceed the values observed in pure diesel operations because of the increased premixed nature of the combustion reaction.

The exhaust gas analysis of a dual fuel engine normally indicates that appreciable proportions of the fuel gas can survive the combustion processes.

Figure 14 shows the behavior of C\textsubscript{x}H\textsubscript{y} (total hydrocarbon, HC) emissions, when the engine uses pure diesel and mixtures of natural gas and diesel. The results indicate that the HC emissions of the gas-fuelled engine are higher than those detected during pure diesel fuel operation at lower loads (<100 kW). Hydrocarbon emissions increase due to several factors, including quenched, lean combustion, wall wetting, cold starting and poor mixture preparation (Nwafor, 1994). Heywood (1988) reports values of HC emissions (as C1) that can reach 3000 ppm or 0.3%, depending on the engine type and work conditions, in agreement with the approximate values of 0.2% at 2000 rpm, 80% of load and 80% of substitution rate reported by Papagianakis and Hountalas (2003), and with Mansour et al. (2001), for conditions of 1800 rpm, 140 kW and unknown diesel substitution rate.

Release of SO\textsubscript{2} directly depends upon the percentage of sulfur content present in the fuel. The contents of sulfur dioxide were very low for any condition of fuel used, as can be observed in Figure 15. It was verified that for loads level up to 70 kW, when pure diesel is used, the gas analyzer identified a maximum percentage of 0.0015%, in the load of 10 kW. For the condition diesel/gas, the percentage of SO\textsubscript{2} in the exhaustion gases is zero for any load condition, indicating a characteristic of no pollution by sulfur compounds when using
natural gas (thus reducing the problem of acid rain).

This unique behavior of SO$_2$ is in disagreement with the several consulted publications, in that the present measurements suggest a decrease in the production of SO$_2$ in the engine, while an increase of this pollutant was expected as a function of increasing load (more fuel input is required at higher loads). Such fact can only be justified in terms of good accuracy of the gas analyzer to measure this component. However, provided these values are valid, there occurs a decrease in the level of emission of this pollutant in the dual mode, due to the expected decrease in the concentration of sulfur in the diesel-gas natural mixture, according to Uma et al. (2004).

4. CONCLUSIONS

The emissions characteristics of a commercial diesel engine operating with natural gas and pilot diesel injection were investigated. Based on the results, the following conclusions were obtained:

a) The value of CO emissions for the engine operating in dual mode is approximately 0.075% for the load of 140 kW, compatible with the literature, but higher than the value measured when the engine operates with pure diesel (approximately 0.012%). The emission of CO was 1.134 g/kWh at 150.5 kW.

b) The value of CO emissions is approximately 6% for all cases examined (diesel and dual mode) for the load of 140 kW. There was reduction of emission of CO$_2$ when the engine operated with the diesel and gas mixture, for loads lower than 110 kW.

c) When the engine operates in dual mode, the concentration of NO$_x$ (NO + NO$_2$) presented lower values than those obtained when the engine worked with pure diesel (0.065%) for loads up to 110 kW, and increasing at higher loads, reaching values as high as 0.10% for a load of 140 kW. The emission of NO$_x$ reached the value of approximately 10.3 g/kWh, in the load approximately equal to 150,5 kW, when operating in dual mode, with substitution rate of 78.7%. When the engine operates with pure diesel, the value was 6.5 g/kWh.

d) The concentration of unburned hydrocarbon (C$_x$H$_y$) in the exhaust gases presented values lower than 0.17% for all loads, regardless of the mode of operation of the engine (dual or pure diesel).

e) Nevertheless, the SO$_2$ emissions decreased a behavior which was observed when the engine operates in dual mode; this important result indicates a lower sulfur concentration when the engine operates in the dual fuel mode.

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