EXPERIMENTAL STUDY ON DIESEL ENGINE: THE EFFECT OF DUAL FUEL OPERATION ON EXHAUST EMISSIONS

Yoge Jerônimo Ramos da Costa, yoge@dem.ufcg.edu.br
Antonio Gilson Barbosa de Lima, gilson@dem.ufcg.edu.br
Marcelo Bezerra Grilo, marcelogrilo@dem.ufcg.edu.br
Celso Rosendo Bezerra Filho, celso@dem.ufcg.edu.br
Mechanical Engineering Department, Center of Sciences and Technology, Federal University of Campina Grande

Antonio Marcus Nogueira Lima, amnlima@dee.ufcg.edu.br
Eletrical Engineering Department, Center of Eletricity and Informatic, Federal University of Campina Grande

Abstract. *The goal of this research is to study the emission characteristics of a commercial diesel engine being operated with natural gas and diesel. The diesel engine sistem is equipped with a diesel-engine CUMMINS 6CTA8.3 of 188 kW at 1800 rpm compled dectrical generator (alternator) ONAN GENSET of 150 kW. An ALPHA OHMIC charge bank was used for evaluating the engine performance. The exhaust gases are also monitored through a KM9106 gas analyzer made by KANE INTERNATIONAL LIMITED. The diese- engine sistem is equipped with electric charge bank, pressure and temperature sensors, gas, air and diesel, flow meters, gas analisis probe and data acquisition system. Emissions of* CO_2, *CO,* NO_2, *NO and* C_xH_y *were measured for differents loads. It was verified that* CO_2, *CO and* NO_x *(NO+*NO_2*) emissions increase in dual fuel operation at all loads as compared to the values obtained to pure diesel operation. Emission concentration in dual fuel and diesel modes are compared with values reported in the literature.*

Keywords : Dual engine, Emissions, Internal combustion engines.

1. INTRODUCTION

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

The use of alternative gaseous fuel in diesel engine is increasing worldwide. The application of engines employing gaseous fuels for power production in dual diesel engine, 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 attractive prices. This is also motivated by a lower maintenance costs, longer engine life following developments in cryogenic technology to store and transport the fuel e economically in liquefied form. Natural gas satisfies the previous requirements as a result of its worldwide usage. Moreover, it mixes uniformly with 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, then some type of ignition aid is required (Mbarawa et al. 2001).

In dual-fuel engines, a carbureted mixture of air and high octane index gaseous fuel (natural gas) is compressed and then fired by a liquid fuel injection which ignites spontaneously at the end of compression phase, using this way the difference of flammability of two fuels. The presence of the gaseous fuel influences both the pre-ignition and post-ignition processes in a complex manner, depending mainly on the fuel used, its concentrations, and operating conditions (Karin, 1980). Many researches has been related 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; Sheti and Salariya, 2004; Payri and Gaurdiola, 2005; Costa, 2007).

Experimental investigations to measure the performance of, and emissions from, a diesel engine are complex, time consuming, and costly. Diesel exhaust emissions influence air pollution significantly. Especially, NO_x, smoke and SO_2 emissions have damaging effects upon the environment and people. Therefore, in the care of the internal-combustion engine, decreasing the level of exhaust gas emissions is always regarded as an important target to be achieved.

In this sense, the aim of this experimental work is to examine the level of exhaust emissions of a dual-fuel (natural gas and diesel) diesel engine.

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 representatives of typical commercial fuels supplied in Campina Grande Cite, Paraiba State, Brazil. As observed, methane is the main constituent of the natural gas resulting to a relatively big octane number, which makes it suitable for engine of high compression rate.

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

Fuel (source)	Chemical composition (in volume)						
Diesel (Medeiros et al., 2002)	$C_{12}H_{26}$ 98,53 %	S 1,47 %					
Natural gas (PBGAS, 2006)	CH_4 89,42%	C_2H_6 7,24%	C_3H_8 0,16%	C_4H_{10} 0,18%	N_2 1,27%	CO_2 1,66%	O_2 0,08%

2.2. Experimental apparatus and procedures

2.2.1. System description

a) The electro-mechanical system

The electric-mechanical system is composed by an turbo charger diesel-engine CUMMINS 6CTA 8.3 l with mechanical power of 188 kW to 1800 rpm, coupled to a generator Onan Genset of 150 kW. The unit is totally scored with air, gas and diesel flow meters, temperature and pressure sensors in several points of the system and probe for analysis of gases. All the data are collected in real time through data acquisition system. Figure 1 presents the electro-mechanic system composed by the diesel engine of six cylinders in line, with power of 188 kW, coupled to the electric generator.

Figure 1. Diesel engine-Electrical generator system

b) The data acquisition system

The data acquisition system is composed by a reading unit and sign treatment, and a personal computer Pentium 4 that has as function to process and to store all of the information collected in real time. Figures 2 and 3 illustrate the graphical interface of the acquisition system developed in ambient MATLAB and the data acquisition system, respectively.

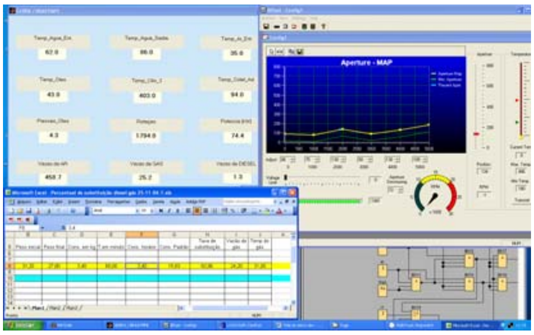


Figure 2. Graphical interface of the acquisition system and data storage.

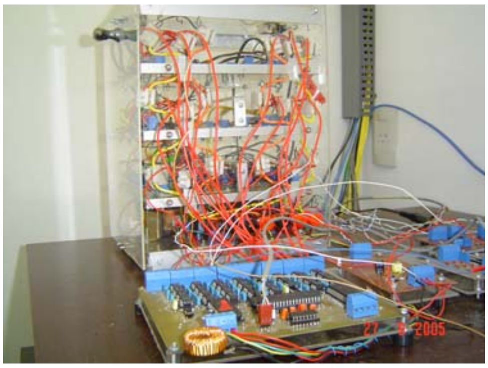


Figure 3. Data acquisition system.

c) System for power measurement in the engine-generator

For obtain the mechanical power in the engine, the electric power system is measured in the generator, through a bank of load resistive ALPHA OHMIC, with capacity of 150 kW. The Figure 4 display the load bank installed and linked the generating unit.

Figure 4. Bank of electrical load with capacity of 150 kW.

d) The gas analysis system

According to evaluate the pollutant emission of the diesel engine operated in conditions previously established, it was used an analyzer of gases manufactured by Kane International Limited, model KM 9106. The Figures 5, 6 and 7 show the analysis unit of combustion gases, 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 equipped with a dual-fuel conversion kit (Figure 8). The kit allowed for engine operation on either 100 % diesel fuel or in a dual-fuel mode. The natural gas was introduced into the intake air system. This way the original characteristic of the diesel engine has not been modified.

Test have been performed for many electrical power in the electrical load bank, in the speed of 1800 rpm and diesel replacement rate changes from 82,28 % in 11,8 kW increasing to 88,4% in 110 kW and decreasing to 83,50 % in 130 kW. A pilot experiment was first conducted to finalize parameters such as duration of experiment, flow rate of gas, air and diesel for each load. During the pilot test the engine was started and waited 15 minutes to start the emissions measures. This time allows the engine to stabilize. Other details about the experimental apparatus and procedures can be found in Costa (2007).

Figure 5. Gas analyzer

Figure 6. Control unit of the analyzer.

Figure 7. Probe of the gas analyzer

Figure 8. Conversion kit

3. RESULTS AND DISCUSSIONS

3.1. Analysis the pollutant emission

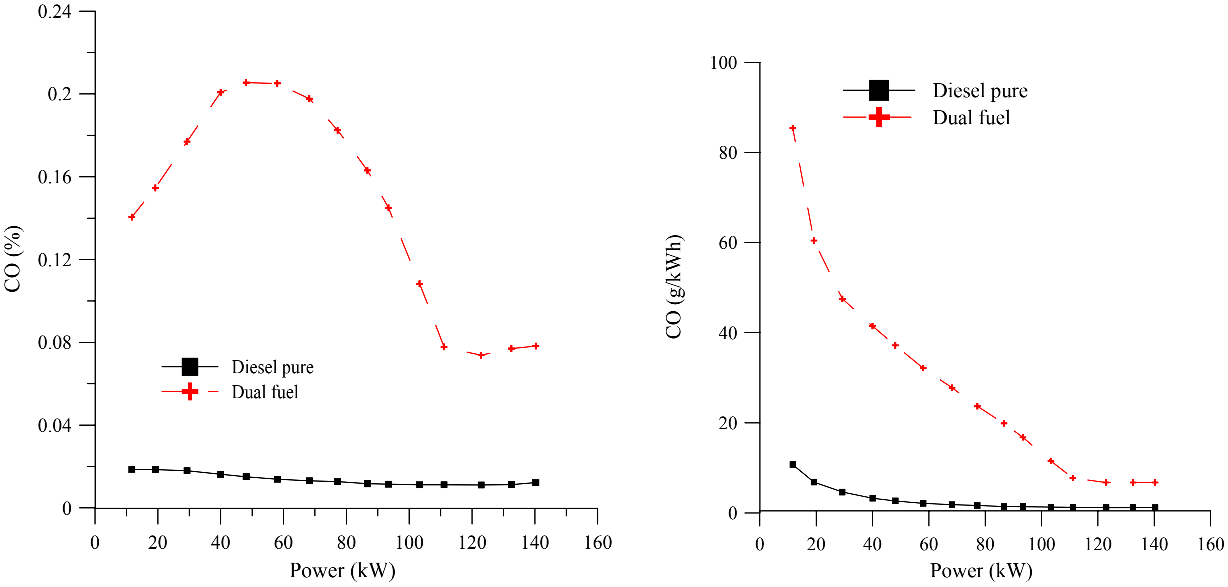
Results of emissions measurement for the engine in diesel alone mode and dual fuel mode are presented and a briev discussion on the results are given.

Figure 9 display the behavior of the emissions concentration of carbon monoxide for several conditions of load of the engine and diesel replacement rate. For the engine operating with 100% diesel, it can be observed that it happens a decrease of CO with an increase of the power, which is waited in the case of diesel cycle engine, seen to be this engine a low originator of CO. CO emissions were increased for natural gas fueling, according to Mansour et al. (2001). In the dual mode, the load on the engine was increased the percentage of CO increased strongly and reached a maximum value of 0,2055 % 84,5 % and load of 50 kW and them started decreasing, which showed deterioration of combustion at higher loads.

At smaller loads the quantity of fuel supplied was small, ie, the mixture remained lean which produced lesser than heat in the chamber resulting in lower flame temperature consequently lesser 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 for producer gas operation but for diesel.

Emissions of pollutant depend on the quality and fuel consumption and of the type of engine in study. For different load conditions, the fuel consumption varies, besides, in the same load and in different operation conditions (pure diesel and in dual mode) the specific consumption varies, so, to compare pollutant emissions is a difficult task, however, to have an idea, some results obtained will be compared with results supplied in the literature. All the results obtained has, occurred in stable operation (non-knocking). The exhaust gas temperature changes from 248 ^{o}C to 435 ^{o}C.



a) b)

Figure 9. Carbon monoxide emissions as a function of the load of engine to 1800 rpm

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

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

Figure 10 shows the effect of load in the emission of carbon dioxide. We can observe in that the level of emission of CO_2 increase with the increase of the load. This factor gives information of the quality of the combustion, indicating a larger efficiency to highest level of this component and a decrease of the level of CO emissions. Higher percentage of CO_2 in the exhaust gas indicated higher oxidation of fuel at the constant engine speed, and release of more heat for power conversion, and better combustion as more was converted from CO to CO_2.

Mansour et al. (2001) report concentrations of $CO_2 \approx 4.5\%$ to 1800 rpm and 140 kW for unknown substitution rate. These values show a good approach with the results obtained in this work (approximately 6.0% for rate substitution of 82%).

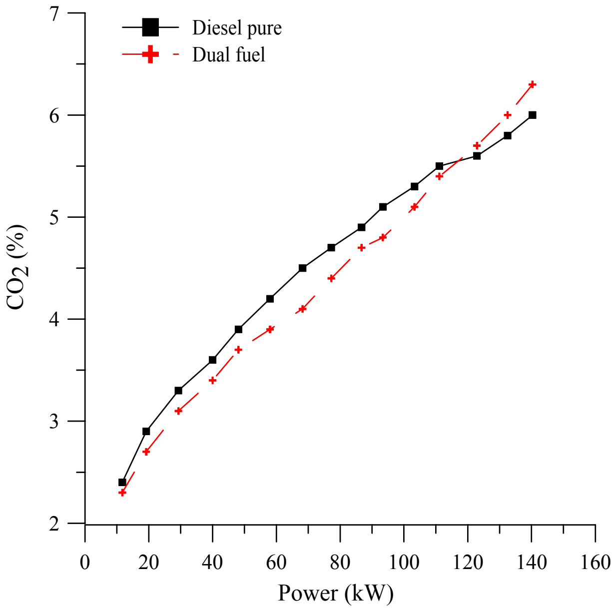


Figure 10. CO_2 emissions as a function of the load engine to 1800 rpm.

Figure 11 shows the effect of load in the emissions of nitrogen oxides. For the situation of the engine operating with diesel pure (Figure 11), it is observed a big increase of the NO emission in the 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 favored in general by the increased oxygen concentration in presence of higher temperatures. Therefore, at lean fuel-air rations 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, because of extending the delay period more and more into the expansion stroke (Karin, 1980).

Papagiannakis and Hountalas (2003), using a four cycle diesel engine, working to speed from 1000 to 3000 rpm, and with loads that varied of 40, 60 and 80% of the full load of the engine, they inform that the percentage of NO for a condition of 2000 rpm, 80% of load and substitution rate of 80%, is of 0.05 %. Mansour et al. (2001), for a condition of 1800 rpm and 140 kW, reports a NO_x ($NO + NO_2$) concentration of approximately 0,050%, for an unknown substitution rate.

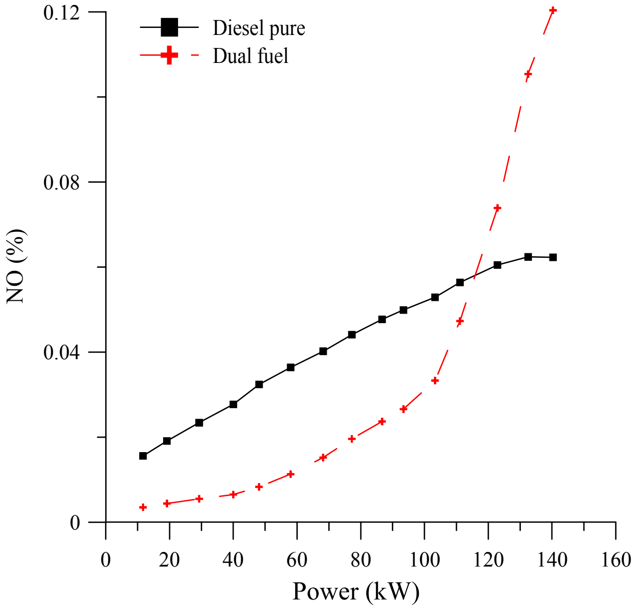


Figure 11. NO emissions as a function of the load engine to 1800 rpm.

Figure 12 shows the effect of load in the emissions of nitrogen dioxides. For load values of up to 100 kW, the emission levels are in agreement with the Standard 315 of CONAMA (Brazil legislation), for the conditions diesel pure (5.0 g/kWh) (see Figure 13). Increase in NO_x emissions level with increase in load was observed because NO_x emissions are very much dependent on combustion chamber temperature. According to Sethi and Salariya (2004), at the higher chamber temperature the reaction $N_2 + O_2 \rightarrow 2\ NO$ takes place. Temperature drops quickly during expansion and exhaust stroke, but the reverse reaction or dissociation of NO is not rapid enough to establish equilibrium and therefore higher amount of NO_x appears in the exhaust gases at higher loads.

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

According to Karim (1980), a low decrease in NO_x concentration is expected for low fuel-air ratio. With further enriching of the gas-air ratio, NO_x concentration increase with a decreased rate compared to diesel operation, until the effective flammability limit is reached. At high loads, NO_x concentrations may even exceed well past the values observed in pure diesel operations because of the increased premixed nature of the combustion.

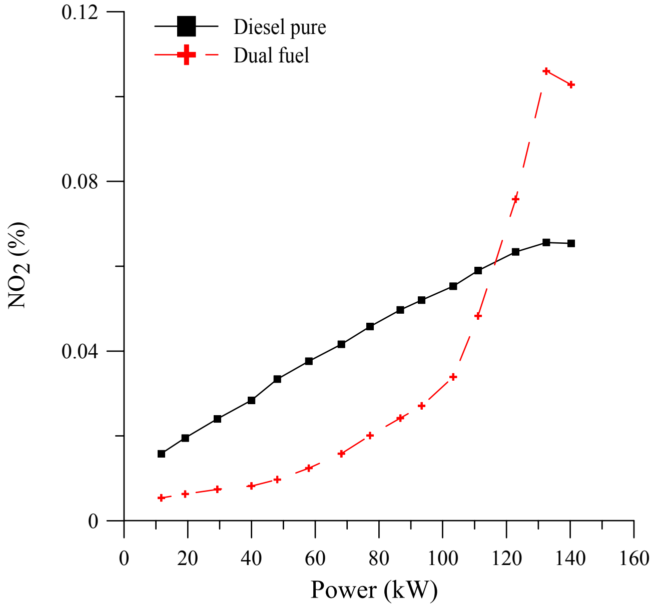
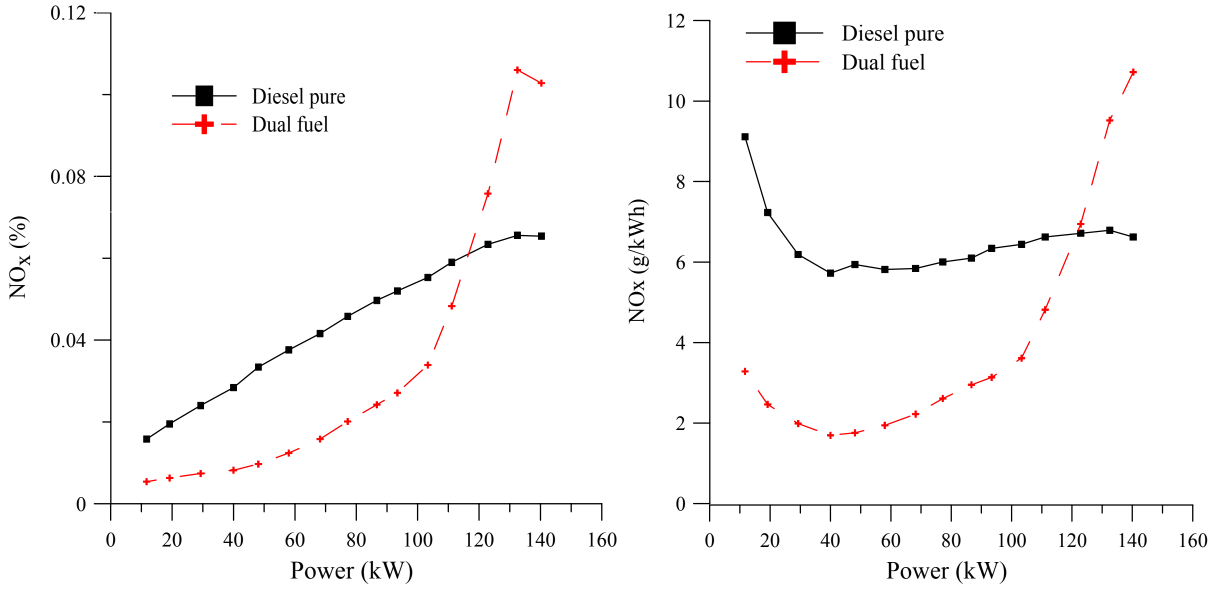


Figure 12. NO_2 emissions as a function of the load engine to 1800 rpm.



a) b)

Figure 13. NO_x emissions rate as a function of the load engine to 1800 rpm.

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_xH_y (total hydrocarbon) emissions, when the engine uses diesel pure and mixtures gas natural and diesel. The results indicate that the HC emissions of the gas-fuelled engine are higher than that in pure diesel fuel operation to lower loads (<100 kW). Hydrocarbon emission increase due to several factors, including quenched, lean combustion, wall wetting, cold starting and poor mixture preparation (Nwafor, 2000). Heywood (1988) report values of HC emissions (as C1), that can reach to 3000 ppm or 0.3%, depending on the engine type and work conditions, in agreement with the values approximately 0.2% to 2000 rpm, 80% of load and 80% of substitution rate presented by Papagianakis and Hountalas (2003), and with Mansour et al. (2001), for condition of 1800 rpm, 140 kW and unknown diesel substitution rate.

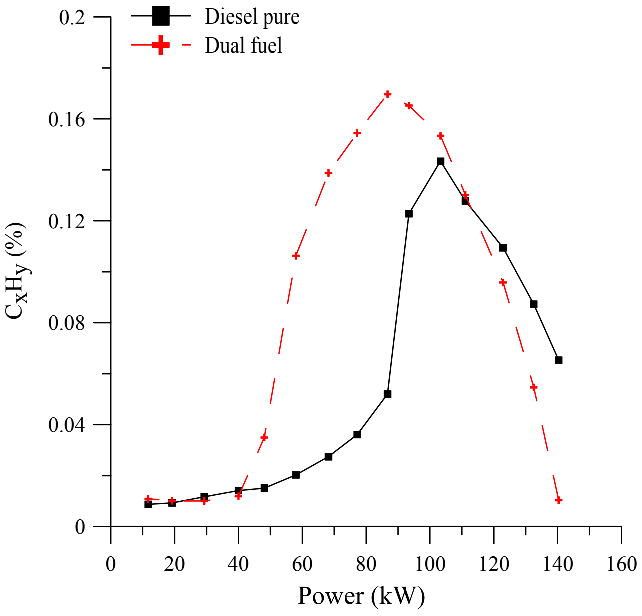


Figure 14. C_xH_y emissions as a function of the load engine to 1800 rpm.

Release of SO_2 directly depends upon the percentage of sulphur content present in the fuel. The presence of sulfur dioxide is very small for any condition of fuel used, as we can observe in the Figure 15. It is verified that for level loads until 70 kW, in the condition diesel pure, the gas analyzer gets to identify a maximum percentage of 0.0015%, in the load of 10 kW. For the condition diesel/gas, the percentage of SO_2 in the exhaustion gases is zero for any load condition, indicating a characteristic of no pollution for components of sulfur in the natural gas (acid rains).

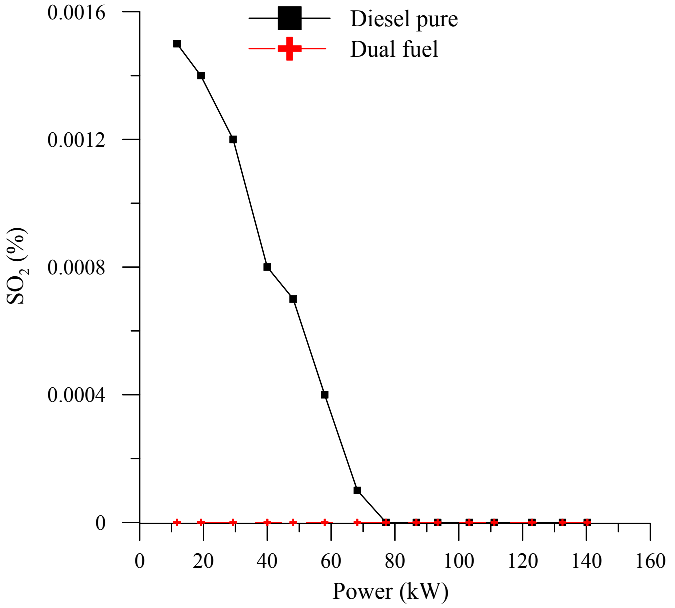


Figure 15. SO_2 emissions as a function of the load engine to 1800 rpm.

This behavior of SO_2 is in disagreement with the several consulted publications, because these measurements presented a decrease in the production of SO_2 for the engine, while it is known that the expected is a increase of this pollutant as a function of the increase of the load (more fuel input is required at higher loads). Such fact can only be justified inaccuracy of the gas analyzer to measure this component. However it is valid this values, it occurs a decrease of the level of emission of this pollutant in the dual mode, for due to the decrease of the concentration of the sulphur in diesel-gas natural mixture, according to Uma et al. (2004), what is waited.

4. CONCLUSIONS

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

a) CO emissions for the engine operating in a dual mode, present values of approximately 0.075% for the load of 140 kW, compatible with the literature, however high than measured value when the engine operates with pure diesel (approximately 0.012%). The emission of CO was in 1.075 g/kWh in the power of 140.3 kW.

b) CO_2 emissions show values of approximately 6% for all of the cases analyzed (diesel and dual mode) in the load of 140 kW. There was reduction of emission of CO_2, when the engine operated with diesel and gas mixture, for load less than 110 kW.

c) When the engine operates in the dual mode, the concentration of NO_x ($NO + NO_2$) it presented lower values those obtained when the engine worked with diesel pure (0.065%) for loads of up to 110 kW, and overcoming for larger loads, reaching values of 0.10% for load of 140kW. Emission of NO_x reach the value of approximately 14.2 g/kWh, in the load of approximately 140 kW, when did the engine operate in the dual mode, with substitution rate of 78.7%. When the engine operated with diesel pure the value was of 5.7 g/kWh.

d) The concentration of hydrocarbon unburned (C_xH_y) in the exhaust gases it presented lower than values to 0.17% in all of the loads, independent in the mode of operation of the engine (dual or diesel pure).

e) Values of SO_2 emissions leave to want, however, the decreasing behavior of this pollutant one when the engine operates in the dual mode, it is correct and it indicates a smaller sulfur concentration when the engine operates in the dual fuel mode.

5. ACKNOWLEDGEMENTS

This work is supported by fund of GEBRA, BRASYMPE and CNPq. The authors would like to thank to the researches reported in the paper that contributes for its improvement.

6. REFERENCES

BI, H.; AGRAWAL, A. K. 1998, "Study of auto-ignition of natural gas in diesel environments using computational fluid dynamics detailed chemical kinetics", Combustion and Flame, Vol. 113, pp. 289-302.

COSTA, Y. J. R. "Energetic and exegetic analyzes of internal combustion engine operating with diesel and natural gas mixture". 2007. 182p., Ph.D. Thesis. Doctorate in Process Engineering. Center of Sciences and Technology, Federal University of Campina Grande.

HENHAM, A.; MAKKAR. M. K. 1998, "Combustion of simulated biogas in a dual-fuel diesel engine; Energy Conversion and Management", Vol. 39, No. 16-18, pp. 2001-2009.

HEYWOOD, J. B. 1998, "Internal combustion engine fundamentals", McGraw-Hill, New York, 930 p.

KARIM, G. A. A, 1980, "Review of combustion processes in the dual engine – the gas diesel engine", Program Energy Combustion Science, Vol. 6, pp. 277-285.

MANSOUR C.; BOUNIF A.; ARIS, A.; GAILLARD, F., 2001, "Gas-diesel (dual-fuel) modeling in diesel engine environment", International Journal of Thermal Science, Vol. 40, pp. 409-492.

MBARAWA, M; MILTON, B. E.; CASEY, T.C., 2001, "Experimental and modeling of natural gas combustion ignited by a pilot diesel fuel spray", International Journal of Thermal Science, Vol. 40, pp. 927-936.

MEDEIROS, M. A. O.; ARAÚJO, A. S.; FERNANDES, N. S. 2003, "Estudo comparativo das propriedades físico-químicas do óleo diesel combustível nos estados do RN e PB", In: 2º Brazilian Congress of R&D in Petroleum and Gas. Rio de Janeiro, Proceedings…, CD-ROM.

NWAFOR, O. M. I.; RICE, G., 1994, "Effect of advanced injection timing on the performance of natural gas in diesel engine", Sãdhanã, Vol.25, Part I, pp. 11-20.

PAYRI, F.; GUARDIOLA, C., 2005, "Trends in automotive diesel engines' design", Proceeding 18º International Congress of Mechanical Engineering. Ouro Preto.

PAPAGIANNAKIS, R. G.; HOUNTALAS, D. T. 2003, "Experimental investigation concerning the effect of natural gas percentage on performance and emissions of a dual fuel diesel engine", Applied Thermal Engineering, Vol. 23, pp. 353 – 365.

PBGAS, 2006, "Report f the gas natural properties supplied in Paraíba. Dec 15 2006. <http://www.pbgas.pb.gov.br>.

REITZ, R. D.; RUTLAND, C. J., 1995, "Development and testing of diesel engine cfd models", Program Energy Combustion Science, Vol. 21, pp. 173-196.

SHENGHUA, L.; LONGBAO, Z.; ZIYAN, W.; JIANG, R., 2003, "Combustion characteristics of compressed natural gas/diesel dual-fuel turbocharged compressed ignition engine" , Dec 20 2006, <http://www.paper.edu.cn>.

SHETI, V. P.; SALARIAY, K. S., 2004, "Exhaust analysis and performance of a single cylinder diesel engine run on dual fuels". Dec 15 2006. <http://www.ieindia.org/publish/mc/0404/apr04mc1.pdf>

UMA, R.; KANDPAL ,T.C.; KISHOREA, V.V.N. 2004, "Emission characteristics of an electricity generation system in diesel alone and dual fuel modes". Biomass and Bioenergy, Vol. 27, pp. 195-203.