EXPERIMENTAL EVALUATION OF GAS TURBINE EMISSIONS FUELLED WITH BIODIESEL AND BIODIESEL-DIESEL BLENDS

Ricardo Wallace Machado Ferreira, ricardowallacemf@gmail.com
Manoel Fernandes Martins Nogueira, mfmn@ufpa.br
Danielle R. S. Guerra, daguerra@ufpa.br
Department of Mechanical Engineering, Federal University of Pará, Belém – Pará, Brasil, CEP 66075-110

Pedro Teixeira Lacava, placava@ita.br
Department of Propulsion, Aeronautical Institute of Technology, São José dos Campos, SP, Brasil, CEP 12228-900

Abstract. *Over the past years many researchers have been carrying out studies regarding the use of renewable fuels for internal combustion engines due the environmental and economic aspects. These studies have been conducted mainly applying biodiesel from vegetable oil or animal sources in compression engines. On the other hand, biodiesel can also be used as fuel for gas turbine despite the scarce amount of work that exists on the literature about this theme. This work reports results of a micro gas turbine running on biodiesel from vegetable source, blends of biodiesel-diesel (B50 and B70) and compare such results with natural gas performance data, specifically the gas composition. The micro gas turbine was originally designed to operate with natural gas. Impact on the nozzle atomization was expected when the fuel was changed from gas to liquid. In order to modify the atomizing nozzle to run on liquid fuel, biodiesel and mixture properties were quantified such as density, ultimate and immediate analysis, high heat value HHV and kinematic viscosity. Changes on pressure and mass flow rate at the injector were applied and an operation condition was achieved to run the micro turbine on the desired biofuels mixed with natural gas on such way to preserve the turbines blades integrity.*

Keywords*: biodiesel, gas turbine, emissions*

1. INTRODUCTION

Several researchers have been studied renewable fuels for internal combustion engines; however it is important to remember that alternative fuels can and should be tested in other thermal machines. Currently, several countries including Brazil follow a new trend in the energy sector, the development of distributed generation (DG) with emphasis on small-scale production. Among the various technologies that can be used in distributed generation and in small-scale, micro-gas turbines have become an excellent technology option. Micro-turbines are small thermal machines operating in the Brayton cycle to produce electricity in the range of 20 to 500 kW.

Recently, Park et al. (2009) has investigated the combustion characteristics of palm oil (PME) as an alternative fuel for gas turbines. Experiments and calculation of chemical equilibrium were performed; an investigation of the fuel atomization characteristics using the method of the spray diffraction analysis (LDSA) was carried out. The results show that the adiabatic flame temperature of the PME is almost the same as diesel for the same equivalence ratio, PME shows to have a smaller bright flame and less soot than diesel.

The combustion and emissions of a heat engine using diesel oil are affected by the characteristics of the fuel atomization, Park et al has investigated the characteristics of injection and atomization of SME as a fuel (Soybean oil methyl ester) in a diesel engine and compared these results with the diesel oil. These experimental results were also compared with numerical results of the KIVA-3V code. The characteristics as type of spray penetration, spray area, spray centroid and injection delay were analyzed using images obtained from a visualization system. The author found that the injection pressure increases, the injection delay decreases due to the increased flow rate of fuel by injection pressure. The spray penetration behavior for biodiesel was similar to the diesel and was compared with diesel injection for several conditions and environments. The SMD of biodiesel decreases along the axis of the spray, it is due of an interaction between the spray and the ambient gas that affects the fuel atomization. The droplet size of biodiesel is slightly higher than that of diesel, however the difference between the two fuels is small.

Souza et al. (2009) conducted a theory and experimental study of a biodiesel from vegetable oil used in a flame tube. In that they analyzed the heat transfer rate in several conditions along the furnace and the performance of biodiesel was compared with diesel oil. The heat flow from the burner for each fuel in the direction of the combustion chamber has been evaluated in the same injection pressure. The results showed that the diesel oil has a higher heat transfer rate in most parts exposed to flame, while in the direction that the body of the flame is not present, the heat transfer rate begins to increase. Visually it was found that the products have less dark coloration than the products generated by diesel oil, it was also verified that the burner had no problems with its operation after replacing diesel fuel by biodiesel.

Bolszo and Mcdonell (2009) have been conducted a study on optimization of a gas turbine emissions operating with biodiesel, their study included atomization, vaporization, combustion and emissions of biodiesel compared with the distillated diesel (DF2). The turbine used was a commercial gas turbine Capstone (C30) 30KW known as a microturbine generator, initially its use was as a backup system or for power generation in remote locations. The evaluation of emissions and performance of biodiesel in gas turbines is commonly investigated due the combustion system of a gas turbine be considered simple to adaptations for the use with liquid fuels, the Capstone was designed to operate with various types of liquid fuels.

The results found by Bolszo and Mcdonell (2009) showed that MTG was successfully adapted to operate with biodiesel as fuel; although the change of DF2 for biodiesel without implementing changes at the fuel injection system will result in an increase on NOx emissions. The analysis of the vaporization and atomizing characteristics suggested that even improving the fuel injection system to reduce the levels of NOx emissions it does not reduce emissions below the level of DF2, therefore, another factor must be associated to this reduction which means that would be required further studies related to kinetic chemical mechanisms to provide better understanding of this case.

Öner and Altun (2009) investigated the use of biodiesel and its blends on direct injection diesel engine. The production of biodiesel from inedible animal fat by the transesterification process and its use in diesel engines, were studied. In this investigation chemical properties of fuel, density and viscosity were obtained according to ASTM D6751 and EN 14214. The biodiesel viscosity and density were found close to the value of diesel, the analysis result of the calorific value showed to be slightly lower compared to diesel. The experimental study results show that the addition of biodiesel to diesel promotes a decrease of the engine efficiency and an increase of the specific consumption. This is due to the low calorific value of the biodiesel compared to diesel. Emissions of carbon monoxide (CO), nitrogen oxide (NOx), sulfur dioxide (SO2) and soot were reduced by about 15%, 38.5%, 72.7% and 56.8 % respectively. The results also showed that it is possible to use biodiesel on direct injection engines promoting the control of air pollution.

Nascimento et al. (2008) conducted a study of performance and emissions in a diesel micro turbine of 30 kW using biodiesel blends as fuel. Also, the authors conducted a simulation cycle using the software GE GATE Cycle for evaluation the micro turbine thermal performance. They found satisfactory results between simulation and experimental investigation. The results also showed that the use of biodiesel promotes a slight increase of CO, low NOx emissions and no emission of SO2. The thermal performance tests showed that pure biodiesel has a specific consumption higher than diesel, during the tests the micro turbine has no failures or difficulties of starting operation when the fuel was replaced.

Hashimoto et al. (2008) investigated the combustion characteristics of Palm Methyl Ester (PME) used in gas turbines. Calculation of chemical equilibrium and the spray characterization using spray analyzer laser diffraction (LDSA) was performed. The obtained results show that the combustion characteristics of the PME are similar to the standard fuel and indicate that the emission of NOx can be reduced by the use of PME. In another study, Hashimoto et al. (2008) investigated the properties of fuels, analyzed the difference in adiabatic flame temperature of the PME and compared them with diesel fuel. Calculation of chemical equilibrium was achieved using CEA code by NASA. The properties of the gas species were obtained from the thermodynamic database (JANAF). The authors found as result that the adiabatic flame temperature of both PME and diesel show a difference greater than 0.6%. An investigation about the atomizing characteristics of diesel and PME shown that there was no significant difference between the flow rate of the fuels. Relation to the average size of drop (SMD) they concluded that PME fuel has fewer tendencies to formation of bright flame and soot than diesel and that for the same SMD and kinematic viscosity the NOx emissions from PME is lower than that of Diesel.

The actual study presents an experimental investigation for determining the behavior of a micro turbine that was designed to operate with natural gas. In the experimental tests the natural gas was change by biodiesel fuel blends in addition of natural gas. The data collected was analyzed based on the references mentioned above. The obtained results of the tests include the exit emissions and temperature.

2. FUEL PROPERTIES

As the main focus of this study is to evaluate the behavior of a micro turbine operating with an alternative fuel, the determination of some fuel characteristics is important. The development of flexible systems or the adaptation of them to operate with different fuels requires a careful theoretical analysis, since there are many variables to consider such as stoichiometry, dilution, temperature and pressure characteristics of combustion in gas turbines. In the following topics we present the characteristics of the fuels that were used for this study.

2.1. Natural gas

Natural gas is a fossil fuel formed by a mixture of hydrocarbons of low molecular weight, its main component is methane CH_4, on the composition there are also propane C_3H_8, butane C_4H_{10}, pentane C_5H_{12}, hexane C_6H_{14}, isobutane iC_4H_{10} and minority fractions of carbon dioxide CO_2, H_2S hydrogen sulfide, water, nitrogen and mercaptans. The calorific value can vary between 8,000 to 10,000 kcal/m3 depending on the levels of heavy (ethane and propane) and inert gases (nitrogen and carbon dioxide).

In Brazil the composition of natural gas for the commercial purpose is determined by the edict number 104, July 8, 2002 by the National Agency of Petroleum, Natural Gas and Biofuels (ANP). For the experiment will be considered the natural gas composition defined by the same edict 104/2002 using the minimum limits of methane, ethane, propane and butane for the southeast Brazilian region. The composition is shown in the Table 1.

Table 1. Natural gas composition

NATURAL GAS COMPOSITION	
CH_4	86% VOL
C_2H_6	10% VOL
C_3H_8	03% VOL

2.2. Diesel

A fossil fuel from distillated petroleum that has variable concentrations of sulfur, nitrogen and metal compounds, the main constituents of diesel are carbon chains from 6 to 30 atoms. Diesel fuel is composed of paraffinic, olefinic and aromatics formulated by mixing various distillations as diesel fuel, heavy naphtha, light and heavy diesel from various stages of processing the crude oil.

The components proportions in diesel fuel are those that allow the finished product fitted within the specifications set by the ANP. The diesel fuel used in the tests is the same fuel sold to consumers and follows the specifications according to standard ANP 15 OF 03.19.2006.

2.3. Biodiesel and blends

Biodiesel can be produced from various raw materials such as vegetable oils, animal fats, waste oils and residual fats from several processes. It can also be used pure or blended with petroleum diesel at different proportions. In recent years technological developments shows trends for adoption the transesterification as the final process (ASTM - D6751). The biodiesel definition according to ANP is a fuel composed of alquilsteres and long-chain fatty acids derived from vegetable oils or animal fats.

Mixtures (compositions) of biodiesel and conventional diesel fuel are the most commonly products distributed for use in the retail diesel fuel. The system known as Factor B is frequently used to indicate the amount of biodiesel in any fuel mix:

- Biodiesel 100% referred to as B100, while
- Biodiesel 20% labeled as B20
- Biodiesel 5% labeled as B5
- Biodiesel 2% labeled as B2

Following in the table 2 there are some specifications provided by Agropalma on Palmdiesel (PME):

Table 2. Palmdiesel properties

	Palmdiesel	ASTM
Glycerol (%)	_ 0,01	0,02 max.
Total glycerides (%)	0,08	0,24 max.
Carbon residue content (%)	0,04	0,05 max.
Density (g/cm3)	0,843	0,82 - 0,87
Viscosity at 40°C (mm2/s)	3,98	1,9 - 6
Flash point (°C)	135	100
Copper strip corrosion	1	3
Water (%)	0,03	0,05 max.
Ash (%)	0,015	0,02
Acidity (%)	0,03	0,04

2.4. Energetic Characterization

To evaluate the energy capacity of a fuel is necessary to characterize the same one. This characterization is carried out through three procedures: determining the calorific value (HHV), elemental analysis and immediate analysis. The determination of the calorific value quantifies the energy contained in the fuel, which can be the determination of its higher and lower heating value. The elemental analysis quantifies the percentage by weight of the elements C, H, O, N, S and ash contained in the fuel. The immediate analysis determines the moisture, volatiles, fixed carbon and ash.

For the purpose of this work, the energy characterization of the biodiesel samples was carried out. The biodiesel plant was supplied by the manufacturer Agropalma (palmdiesel), the origin plant is derived from palm oil trees. All other fuels used at the micro turbine as natural gas and diesel, had their energy characterization data obtained from the ANP tables as mentioned earlier. The samples of biodiesel were analyzed in the laboratory of biomass characterization (LACBio), located at the Laboratory of Mechanical Engineering, UFPA, in which we performed the following analysis: calorific value and elemental analysis that are presented in Table 3.

Table 3. Palmdiesel elements

Palmdiesel	
HHV(MJ/kg)	39,7083
%C	76,610
%H	12,800
%O	8,715 (1)
%N	0,300 (2)
%S	1,575
Formula empírica	$C_{6,378}H_{12,699}N_{0,021}O_{0,544}S_{0,049}$

3. ATOMIZING CHARACTERISTICS

The atomizing system was designed to use natural gas with liquid fuel (diesel or biodiesel). The atomization characteristics as Sauter mean diameter (SMD), cone angle of the spray were investigated. Figure 1 shows a schematic of the experimental apparatus. The fuel is pressurized by the supply of N2 gas in the fuel tank, the flow rate fuel was measured using a flowmeter from Omel manufacturer, model number 4Q factory calibrated for a flow rate from 0 to 14 g/s for a liquid with density of 850 kg/m3, located in the fuel line before the injector.

The average size of droplets was measured by a laser system (Malvern MasterizerX) in which traverses the spray by a laser beam, initially parallel spreads through photodiode detectors located on a circular plate, collects the scattered light angular sectors individuals. To analyze the distribution of droplet size, the formulation used by the system is the Fraunhofer theory, which states that a parallel beam and monochromatic light passes through cloud droplets. The pattern obtained is of a series of concentric light and dark discs whose spacing between them will depend on the distribution of the droplets. Each detector scans in the order of 2ms, each measure consists of 2,000 scans.

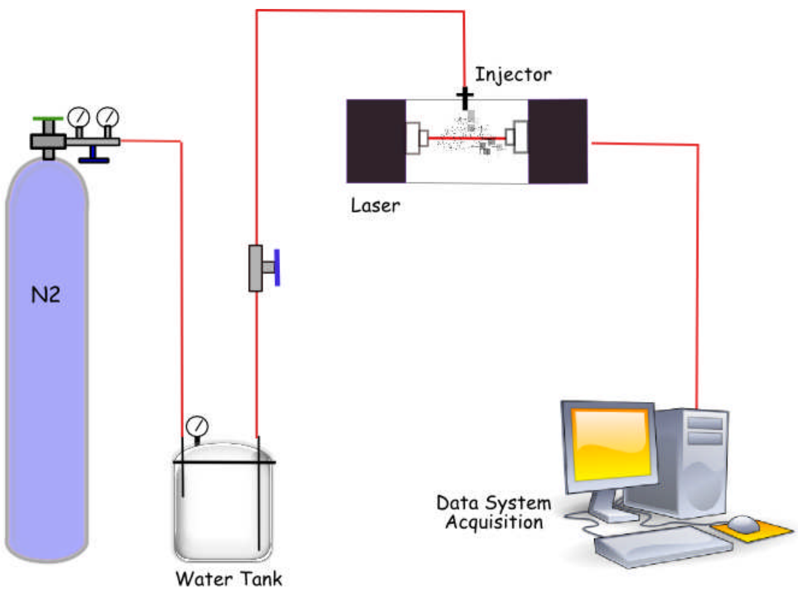

Figure 1. Experimental apparatus of the atomizing system.

4. EXPERIMENTAL APPARATUS FOR COMBUSTION

Figure 2 and Figure 3 shows the experimental apparatus as well as the squematic used in testing the micro turbine. The system of data acquisition and control of MTG is comprised of supervisory software developed at RSView32 platform from Rockwell manufacturer in which it is connected to a programmable logic control (PLC) model MicroLogix 1100. This system receives signals from the transducers, sensors, actuators and controls. Temperatures are measured using a thermocouple type K and one thermocouple T at each position. The operating range of the thermocouple type K is 0 to 350 °C with an error of ± 1 °C and the T-type thermocouple is 0 to 1250 °C with an error of ± 2.2 °C. The thermocouples are connected to an analog module Rockwell where the signals are sent to the PLC.

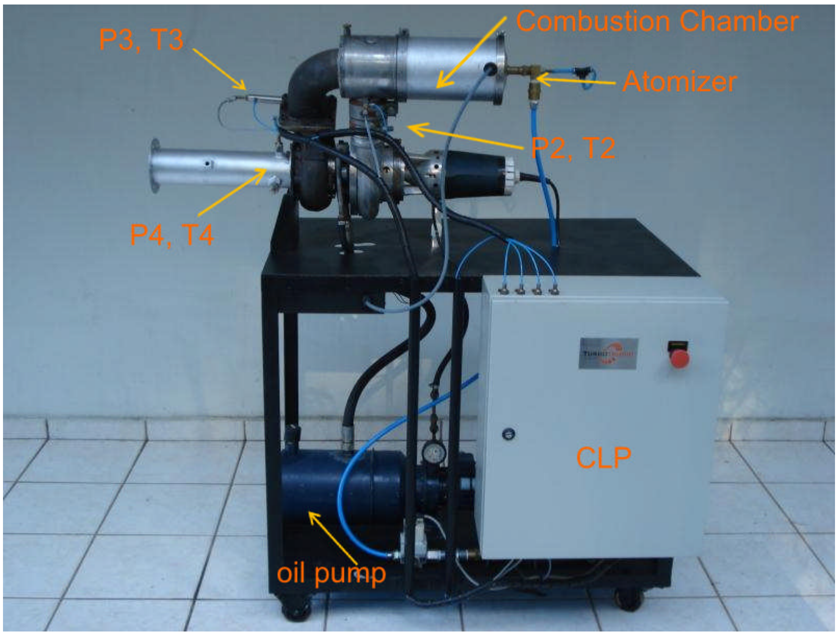

Figure 2. Micro turbine

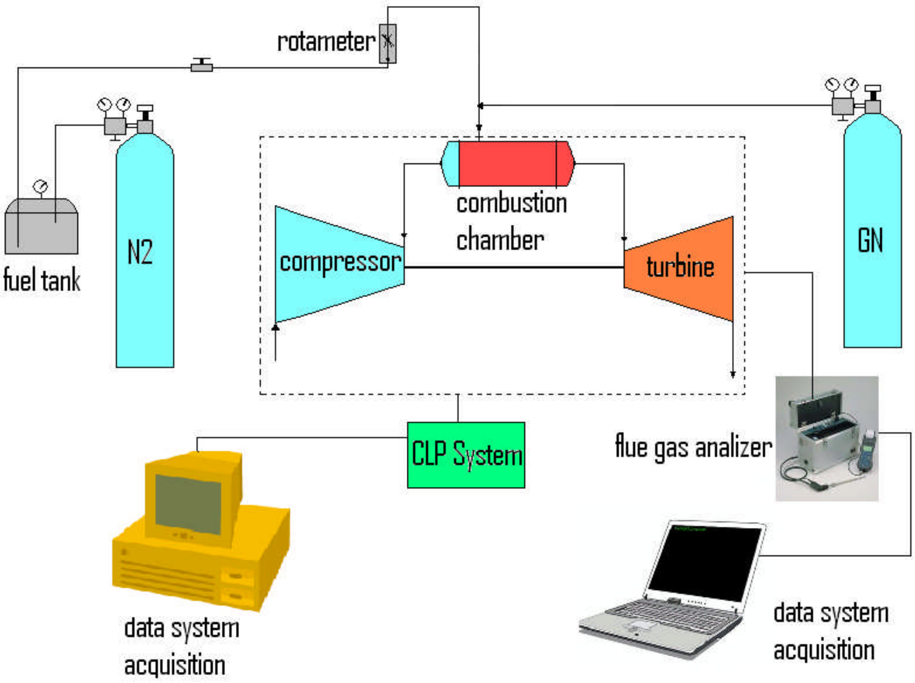

Figure 3. Squematic draw of the experimental apparatus

The pressure measurements at each point shown in figure 2, was performed using a pressure sensor at each position. The sensor has a measuring range from 0 to 6 bar with an error of 1%. The sensors are connected to an analog module Rockwell where the signals are sent to the PLC. The micro turbine rotation is measured by an inductive-type Hall sensor. The counting of pulses is sent from the Hall sensor to a pulse counter Phoenix Contact MCR-f-UI-DC, visualization and control of rotation is made by the supervisory system.

The flow rate of natural gas is measured by an orifice plate; a software receives data from pressure through a pressure transducer and solves the calculations based on data specific obtained from the orifice plate, accounting the flow rate. To account the flow rate of liquid fuel (Diesel, Biodiesel and blends) we used a flowmeter manufactured by Omel, calibrated for a flow rate from 0 to 14 g/s for a liquid with density 850 kg/m3. The flow meter was recalibrated for each fuel in advance before the tests. The emissions data of CO_2, NOx, CO, and O_2 were collected using a gas analyzer 8000 and the Greenline program DBGas2000.

The gas analyzer consists of a main unit (MCU, Main Control Unit) and a remote unit (RCU, Remote Control Unit). The gas is collected in the exhaust of the micro turbine through a tube and sent to the MCU. All the data analysis is done on the MCU which can be configured and controlled remotely through the RCU cable or Bluetooth communication.

5. RESULTS AND DISCUSSION

Figure 4 shows the experimental results measured from SMD, each experimental value is the mean value of 25 samples, with a satisfactory repeatability presented a maximum standard deviation of about 0.96% to 4 atm.

The increase in pressure difference is expected and beneficial to the SMD. This fact causes a liquid discharge at high speed from the atomizer nozzle, providing a thinner spray. However, according to the literature, Wang and Lefebvre, the droplet size presented by our atomizer is in the range of drops greater than 100 micrometers. So, it has a greater vaporization time, increasing the mixing length and the combustion region.

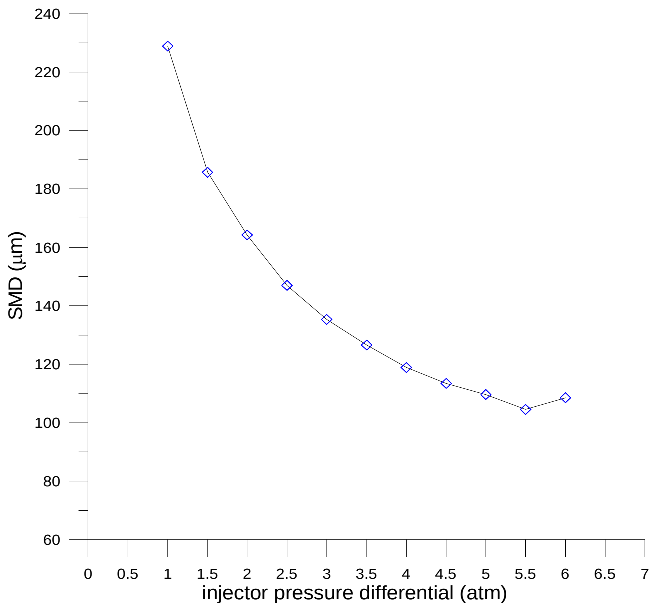

Figure 4. Sauter mean diameter (SMD) as a function of the atomizing pressure.

The cone angle increases with pressure, this is easily expected since with the increase pressure and hence the tangential velocity, there is a tendency for the jet to be thrown over the sides, increasing the angle. We can observe in figure 5 that when the pressure increase occurs an increase in cone angle of the spray, but from a certain pressure difference can be noted that for our atomizer has not increased very significant as we observed in Figure 5, this is due to the geometrical characteristics of the injector.

Emissions analysis and exhaust gas temperature for rotation of 45,000 rpm. For CO_2 Emissions: Figure 6 compares the CO_2 emissions of Natural gas fuel, Diesel, Biodiesel and blends. For all blends was an increase in emissions compared to Natural gas from 17.76% for BDD50, 66.44% for BDD70, 69.97% for BDD100, and 76.97% for diesel fuel.

CO emissions: In Figure 7 there are the CO emissions from Natural gas, Diesel, Biodiesel and blends, for all blends was an increase in emissions compared to Natural gas from 2.53% to BDD50, 2.57% for BDD70, 2.69% to BDD100, and 1.79% for diesel fuel.

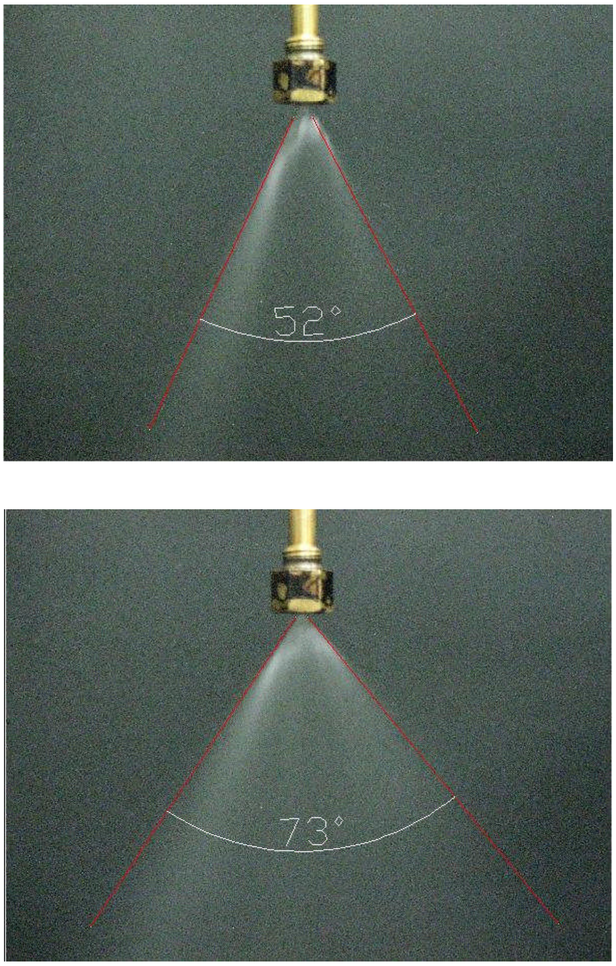

Figure 5. Cone angle of the spray.

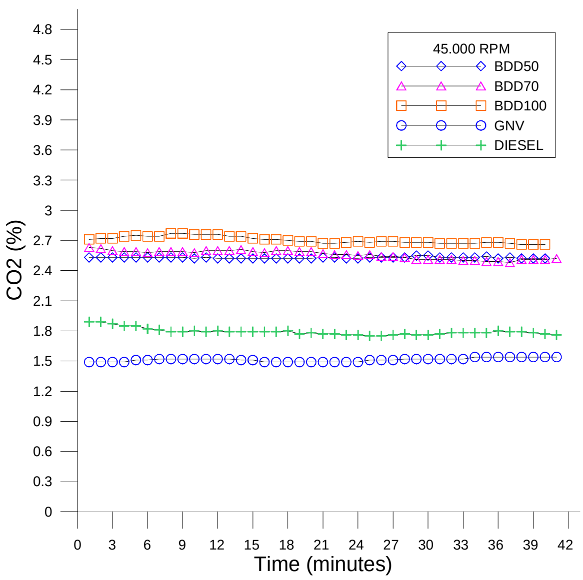

Figure 6. CO2 emissions for the fuels in study.

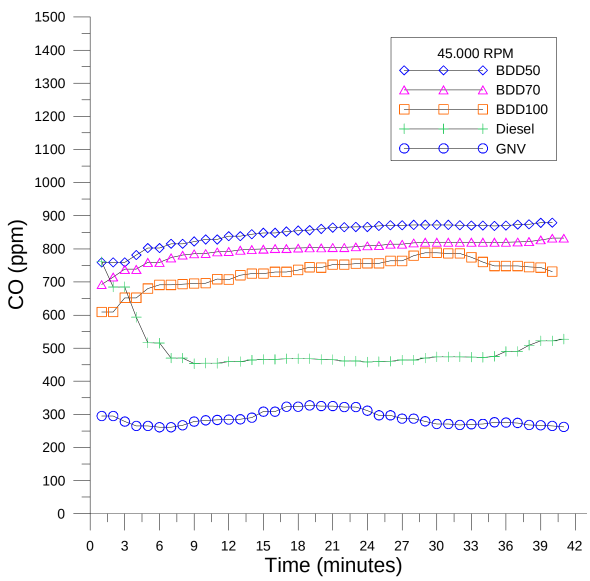

Figure 7. CO emissions for the fuels in study.

NOx emissions in Figure 8: can be observed that there was an increase of 12.5% in emissions compared to Natural gas fuel for Diesel BDD100. For BDD50 and BDD70 remained the same levels of emissions when compared to NG.

Gas temperature in Figure 9: it was observed that for all blends have an increase in temperature when compared to NG. This increase was of 39.40% for BDD50, 60.24% for the BDD70, 72.20% for BDD100, and 69.14% for diesel fuel.

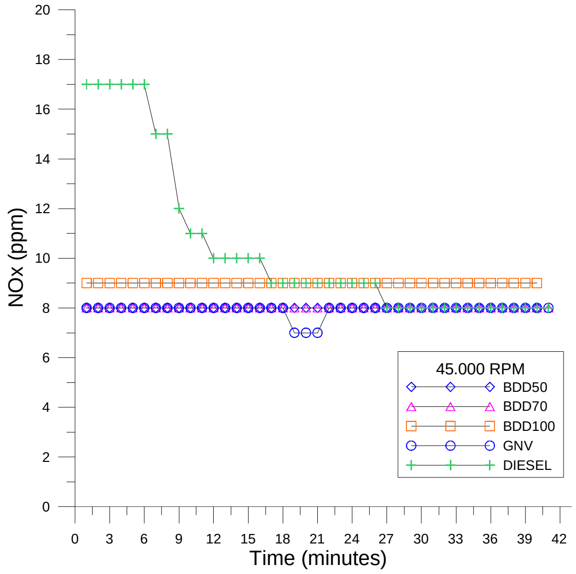

Figure 8. Nox emissions for the fuels in study.

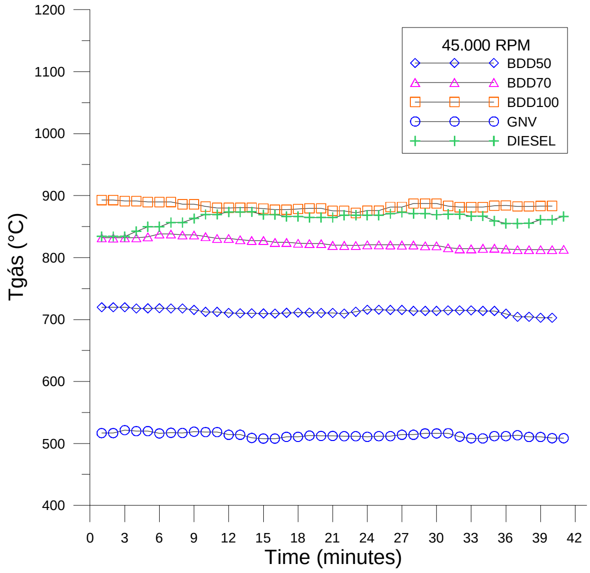

Figure 9. Gas exhausted temperature.

Results also show emissions analysis and gas exhaust temperature for rotation of 60,000 rpm. For CO2 emissions in Figure 10: compares the CO2 emissions of NG, Diesel, Biodiesel and blends, it realizes that for all blends was an increase in emissions compared to NG from 79.59% to BDD50, of 83.67% for the BDD70 of 78.91% for BDD100, and 31.97% for diesel fuel.

CO emissions: Figure 11 compares the CO emissions of NG, Diesel, Biodiesel and blends; it realizes that for all blends was an increase in emissions of 258.0% to BDD50, of 254.68% for the BDD70 of 336.85% for BDD100, and 137.0% for diesel oil.

NOx emissions in Figure 12: can be observed that there was an increase in emissions compared to NG of 77.77% to BDD50, of 55.55% for BDD70, a reduction of 11.11% for BDD100, and an increase of 84.33% for diesel.

Gas temperature in Figure 13: it was observed that for all blends an increase in temperature happen when compared with NG of 34.85% for CNG BDD50, of 63.46% for the BDD70, of 66.98% for BDD100, and 72.84% for diesel oil.

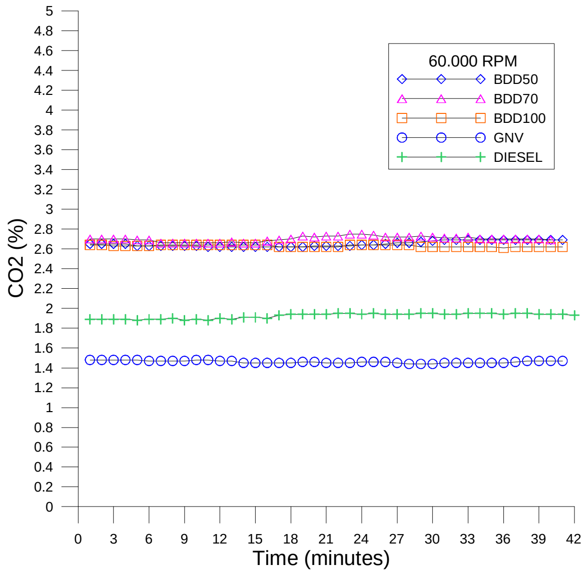

Figure 10. CO2 emissions for the fuels in study.

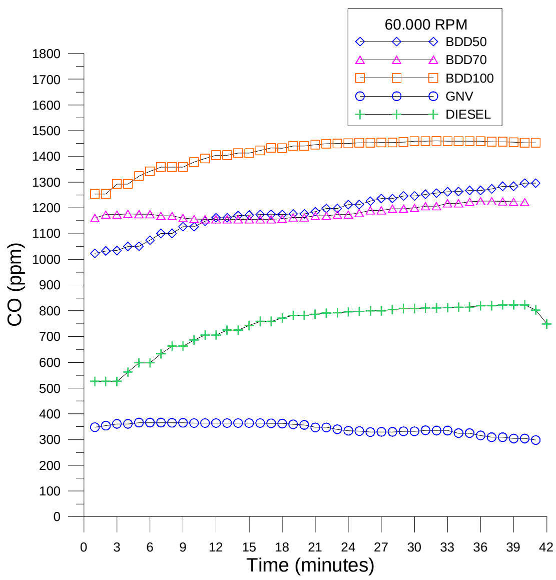

Figure 11. CO emissions for the fuels in study.

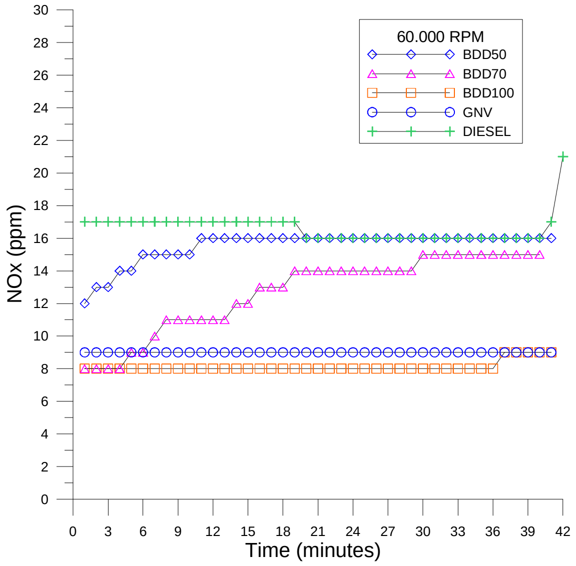

Figure 12. Nox emissions for the fuels in study.

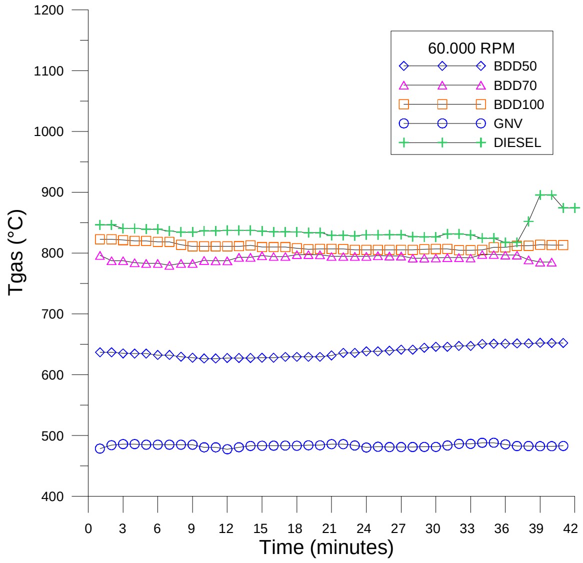

Figure 13. Gas exhausted temperature.

6. CONCLUSION

Analyzing the results presented by of Hashimoto et al. 2008 and Couto et al. 2009, for an atomizing system operating at low pressure swirl the SMD is in the range of 80 to 120 micrometers. So our medium size atomizer drop is larger than that found in the literature, and cone angles were slightly lower for the same variation of pressure.

The emission results are primarily influenced by the equivalence ratio at the primary zone, by the average size of droplet and the geometry of the combustion chamber. Since the combustion chamber was designed to operate with natural gas it has reduced geometries whose impacting on the emissions results for the combustion of liquid fuels like Diesel and Biodiesel.

Based on this statement we can conclude that for the rotation of 45,000 rpm, diesel fuel had lower rates of CO and CO_2, while BDD100 showed lower levels of NOx and temperature of gases. For rotation of 60,000 rpm, diesel fuel had lower rates of CO and CO_2, while BDD50 showed lower levels of NOx and temperature of gases.

However to obtain more conclusive results we should improve the atomizing system and modify the combustion chamber geometry to obtain similar combustion conditions for all fuels in an operating pre-determined conditions. The purpose of this preliminary study was to investigate the feasibility of biodisel and diesel in addition of natural gas as an alternative fuels for gas turbines.

7. ACKNOWLEDGEMENTS

The authors would like to thank PROCAD/CAPES for the research grant provided to carry out this project and Aeronautical Institute of Technology for providing facilities during the course of this study.

8. REFERENCES

Park, S.H., Kim, H.J., Suh, H.K., Lee, C.S., 2009. “A Study on the Fuel Injection and Atomization Characteristics of Soybean Oil Methyl Ester (SME)”. International journal of Heat and Fluid Flow, Vol. 30, pp. 108–116.

Souza, G.R., Santos, A.M., Ferreira, S.L., Martins, K.C.R., Módolo, D.L., 2009, “Evaluation of Performance of Biodiesel from waste vegetable Oil in a Flame Tube Furnace”, Applied Thermal Engineering, Vol.29, pp. 2562-2566.

Bolszo, C.D. and McDonell, V.G., 2009. “Emissions Optimization a Biodiesel Fired Gas Turbine”. Proceedings of the Combustion Institute, Vol. 32, pp. 2949–2956.

Öner, C. and Altun, S., 2009. “Biodiesel Production from Inedible Animal Tallow and an Experimental Investigation of its use as alternative Fuel in a Direct Injection Diesel Engine”. Applied Energy, Vol. 86, pp. 2114–2120.

Nascimento, M.A.R., Lora, E.S., Corrêa, P.S.P., Andrade, R.V., Rendon, M.A.,Venturini, O.J., Ramirez, G.A.S.,2008, Energy, Vol 33, pp. 233-240.

Hashimoto, N., Ozawa, Y., Mori, N., Yuri, I., Hisamatsu, T., 2008, “Fundamental Combustion Characteristics of Palm Methyl Ester (PME) as Alternative Fuel for Gas Turbine”, Fuel, Vol.87, pp. 3373–3378.

9. RESPONSIBILITY NOTICE

The following text, properly adapted to the number of authors, must be included in the last section of the paper: The author(s) is (are) the only responsible for the printed material included in this paper.