

PERFORMANCE EVALUATION OF MICROTURBINES OPERATING WITH SECOND-GENERATION BIOFUELS

O. J. Venturini, osvaldo@unifei.edu.br

D. J. R. Orozco, dimas.rua@unifei.edu.br

J. C. P. Escobar, jocesobar@gmail.com

E. E. S., Lora, silva.electo52@gmail.com

Universidade Federal de Itajubá, Av. BPS, 1303 Itajubá - MG, 37500-903, Brazil

Abstract. *The constant rise in electricity demand has challenge researchers around the world to reduce the costs and increase the availability of the distributed generation systems. At the same time addition, it is possible to observe a growing necessity of diversification of the energy sources used worldwide, due to the scarcity and environmental impact of the traditional energy sources. In this scenario, the second and third-generation biofuels are being viewed as a promising alternative, especially when considering the use of microturbines in distributed generation systems. Microturbines are turbo generators with capacity from 30 and 300 kW. These prime movers can operate with different kinds of fuel, such as gasoline, diesel, ethanol, natural gas and biodiesel. The behavior of microturbines when burning most of these fuels is relatively well known, but is of special interest to determine their performance when operating with biobutanol, lignocellulosic ethanol, diesel from sugar cane and from algae, since the production of second-generation biofuels, and in some cases of third-generation, is already reaching a commercial stage. Thus, the main objective of this paper it to evaluate the performance (efficiency, specific fuel consumption, deviation of the power generated, etc.), for different load conditions, of a 30 kW microturbine when burning biodiesel, sugarcane diesel and biobutanol, as well as to identify possible limitations and necessary modifications for its operation. The analysis was carried out using data obtained from a mathematical model and from an experimental facility built in one of the laboratories of UNIFEI – Univ. Federal de Itajubá.*

Keywords: *microturbines, biofuels, simulation, sugar cane diesel, biobutanol.*

1. INTRODUCTION

The current model for electricity generation around the world is dominated by centralized power plants, which are usually located distant from the consume centers. This scenario requires electricity transmission across the distance between the power plants and the faraway consumers. Likewise, these systems contribute to greenhouse gas emission; have high inefficiencies and power loss over the lengthy transmission lines (Capehart et al., 2003).

In the case of Brazil, despite having a renewable energy matrix, this problem becomes quite significant because around 81% of the electricity is generated in hydroelectric power stations located distant from major centers of consumption. Therefore, in last years it has grown the interest for systems able to generate electricity close to the end users of power. This new electricity generation alternatives can contribute to the reduction of problems related to the geographical distribution of production, reliability and flexibility of operation, availability and prices of fuels, installation and construction time, funding conditions and environmental licensing (Lora e Haddad, 2006).

On this scenario, the industry restructuring process in many countries is exposing the power sector to market forces, which is creating competitive structures for generation and alternative regulatory structures for the transmission and distribution systems. As a result, in the last years many countries introduced changes in their legislation allowing agents of the industrial, commercial and residential sector, which in the past were only consumers of electricity, to generate their own electricity. Brazil opened up this possibility with the publication of the normative resolution ANEEL n° 482/2012, amended by the resolution n° 687/2015, which grants and regulates the access to the Brazilian electrical system by any independent producer (ANNEE, 2015).

Distributed generation technologies are very in different stages of development. A considerable number of power generations systems available in the 1.0 to 10 MW range can already be reliably inserted in existing distribution grids. However, prime movers in smaller sizes (5 to 500 kW) remain more difficult to find, except for internal combustion engines and microturbines. The fuel used to generate power in an internal combustion engine; microturbine and gas turbine may come from a variety of renewable and nonrenewable sources such as natural gas, propane, syngas, biogas, biodiesel, etc.

This work focuses on the assessment of the behavior of one of these small-scale prime movers: the microturbines. Distributed generation using microturbines is accepted as a typical and practical solution because of its environment-friendliness and high-energy efficiency. Various applications such as peak shaving, cogeneration, remote power and premium power will make its penetration more widespread. Microturbines are high-speed prime movers and its mechanical power is transformed into electricity by a permanent magnet synchronous machine, with power range between 15 and 300 kW. The behavior of microturbines fueled with several of above-mentioned fuels is relatively well understood, but it is of special interest to determine their performance when operating with other renewable fuels.

Biodiesel is a renewable fuel with good potential to replace fossil fuels, particularly diesel. Biodiesel is traditionally produced from oleaginous plants, such as: palm oil (*dende*), jatropha carcass (*pinhão manso*), cotton, canola, etc (Koizumi, 2014). There are many reasons of economic, environmental and social character to justify the strategic insertion of biofuel in the Brazilian energy matrix. However, the efficient resources usage on its production chain is an aspect that deserves as much attention as the development of alternative fuels, due to the large tracts of land that some types of crops demand for biofuel production. Another important factor to consider is the high production cost of biofuels compared to fossil diesel (Lora and Venturini, 2012). This problem can be compensated using raw materials with low added-value, which does not compete directly with food production and have high availability and/or productivity, such as: beef tallow, sugarcane and algae.

2. SUGARCANE DIESEL

The sugarcane diesel (farnesane) can be classified as a biodiesel being produced from fermentable sugars present in the sugarcane syrup using genetically and metabolically engineered yeast (Conconia and Crnkovica, 2013). The oil produced from the fermentation of sugars is then saturated by the addition of hydrogen molecules. Farnesane, a C15 isoprenoid, is the only single-molecule diesel fuel available (Pisano and Wagonfeld, 2013), although traces of other molecules can be found on the commercial product. Besides being a renewable and Sulphur-free fuel, sugarcane diesel presents indices of quality similar to those determined for samples of fossil diesel. The farnesano, a saturated hydrocarbon (isoparafina) is very resistant to oxidation. In this way, there is low probability of formation of degradation products, such as aldehydes and ketones, as well as compounds with high molar mass, which could enhance the formation of deposits its storage (Milloa et al., 2014).

The sugarcane diesel can be used pure or mixed with fossil diesel or biodiesel in internal combustion engines, without requiring modifications in the calibration or material's composition of the fuel injection system. Despite the sugarcane diesel have lower density than the range established by utilization codes (ANP, 2011), the fuel is technically suitable for its use pure (100%), showing performance curves similar to fossil diesel.

The commercial sugarcane diesel presents unsaturated compounds content well below the usually verified in biodiesel. It has higher calorific value of 46.91 MJ/kg (average) and cetane number of 58.0 (ASTM D6890), being these values higher than those usually found in fossil diesel, i.e., 44.88 MJ/kg and 48, respectively (Smagala et al., 2013).

The American company Amyris has been gaining attention and respect in the international fuel market, since it has developed a continuous process for diesel production from sugarcane, where through the modification of the yeast used in the fermentation of the must, it is possible to produce a hydrocarbon (C15H24) instead of ethanol (Oliveira, 2008).

3. BIOBUTANOL

In the sugarcane industry, pentose sugars can be used for the production of added-value chemicals or advanced biofuels, like biobutanol. This fuel has attracted the attention of investors due to its potential utilization use as a drop-in biofuel, and to fulfill chemical market demand. The opportunities around butanol, are extraordinarily diverse, and have a real potential to permanently affect the renewable energy and materials landscape (Mariano et al., 2013). Over a dozen companies are focused on developing biobutanol on commercial scale. This is a true biofuel for masses with potential of little or no impact on food supply and ability to compete favorably with \$80 bbl oil.

Biobutanol is second-generation biofuel, which can be produced from the same feedstocks as ethanol (sugarcane, sugar beets, corn and other biomass materials containing cellulose). Butanol is a primary alcohol with a molecular formula of C₄H₉OH, and it is therefore an oxygenated fuel, which has advantages over both ethanol and methanol as alternative fuel for combustion engines (Mascal, 2012).

Currently, gasoline is blended with ethanol at various percentages. However, butanol has several advantages over ethanol, such as higher energy content (HHV = 37.3 MJ/kg), lower water absorption, lower volatility, higher flash point and better blending ability. Butanol is non-corrosive, which means that it can use existing infrastructure such as pipelines, and replace, ethanol or gasoline in transport sector without the need of using additives (Yun et al., 2016).

Mendez et al. (2014) studied the performance and emission characteristics of butanol/Jet A blends in a gas turbine engine. Based on their results it is possible to conclude that the blends of butanol with Jet-A are promising alternative fuels, with performance similar to that of Jet-A, but with less CO and NO_x emissions.

4. BEEF TALLOW BIODIESEL

The beef tallow is formed by saturated fatty acids, having chemical structures similar to those of vegetable oils. The differences are in the types and distributions of the fatty acids combined with glycerol. Thus, the beef tallow is also an option of raw material for biodiesel production, being formed by triglycerides that have in their composition palmitic, stearic and oleic acids, representing approximately 30%, 25% and 45%, respectively, of the tallow components, which are essentials for the production of biodiesel being. Approximately 1560 million tons of beef tallow are produced in the country each year and each kilogram of tallow can generate up to 800 ml of biodiesel. Tallow biodiesel production has

already been approved by the National Petroleum Agency (ANP) and specifications for fuel sales must follow code ANP n° 42 (Barros and Jardine, 2015). In June 2009, beef tallow represented 14.03% of the raw materials used in the agri-fuel industry. Data from ANP (2010) show, at the same time, a large monthly variation in the use of raw materials for biodiesel production, but in total, soybeans and beef tallow represent a significant part of it.

The fats from animal slaughter are attractive for biodiesel production, due to the high quantity of residues produced, meaning low cost and immediate availability of the raw material in agri-industrial areas. In addition, the use of animal fats for biodiesel production contributes to the reduction of environmental impacts, avoiding the improper destination of the residues that would happen if they were not processed. When compared with the biodiesel produced from vegetable oils, the biodiesel from animal fat has advantages such as: increased cetane number, greater stability to oxidation and lower Iodine Number, which is a measure of the degree of unsaturation of an oil or fat. However, beef tallow biodiesel has the disadvantage of having higher cold filter plugging point and higher Sulphur content, if compared to values found in vegetable oils, but this can be offset through its mixture with vegetable oils (Silva et al., 2012).

In this scenario, the search for raw materials alternatives makes room for the beef tallow, the second raw material in the Brazilian production of biodiesel, which accounts for 17% of the biodiesel produced (Martins, 2011).

Considering what was exposed beforehand, this work presents the results of and technical and environmental assessment of a microturbine powered with biofuels, such as: sugarcane diesel (farnesane), beef tallow biodiesel and biobutanol. It was developed a computational model of a 30 kW microturbine, which, after being validated with experimental data obtained in the Lab of Microturbines and Biomass Gasification of UNIFEI, was used to evaluate the behavior of microturbine in different load and environmental conditions.

5. MICROTURBINES

Microturbines are small gas turbines, which burn gaseous or liquid fuels to create high-energy gas stream that drives a turbine (expander) connect to an electrical generator. Usually the capacities of microturbines range from 30 to 300 kilowatts, while conventional gas turbines capacities range from 500 kW to more than 300 MW. They generally have marginally lower electrical efficiencies than similarly sized internal combustion engines, and working under regenerative cycles, their efficiency can be as high as 27 to 33% (Borbely and Kreider, 2001). Simple cycle microturbines have lower efficiency, with values around 18%, but their capital costs are also lower. Microturbines are derived from large turbocharged diesel engines used in trucks or small auxiliary power units (APUs) used in the aviation industry. They usually have a single shaft and single stage radial compressor and turbine, with nominal rotation speeds between 90,000 and 120,000 rpm. Higher capacity units use multistage compressor and turbines, which work at lower rotational speeds. However, because of their design simplicity and relatively fewer moving parts, microturbines have the potential for simpler installation, higher reliability, reduced noise and vibration, lower maintenance requirements, lower emissions, continuous combustion and possibly lower capital costs compared to reciprocating engines (Lora and Haddad, 2006).

To evaluate the behavior of the microturbine operating in design and off-design conditions and also in conditions different from those they were experimentally tested, it was developed a computational model of a 30 kW regenerative microturbine using GateCycle software 6.1.2. Regenerative microturbines have a heat exchanger installed in their exhaust system. In this heat exchanger, the air that leaves compressor is heated by the exhaust gases. This raise in air temperature before it is delivered to the combustion chamber decreases fuel consumption and, consequently, raises microturbine efficiency. Figure 1 shows a scheme of the model developed in GateCycle™ (GE Energy) that was used to simulate the microturbine under study, where it is possible to see its different components, such as: intake ducts and air filters (DUCT1), exhaust gas systems (DUCT2), compressor (CP1), regenerator (HX1), combustion chamber (CMB1), fuel supply (GAS2), expander (turbine) (TRB1) and electric generator (GEN1).

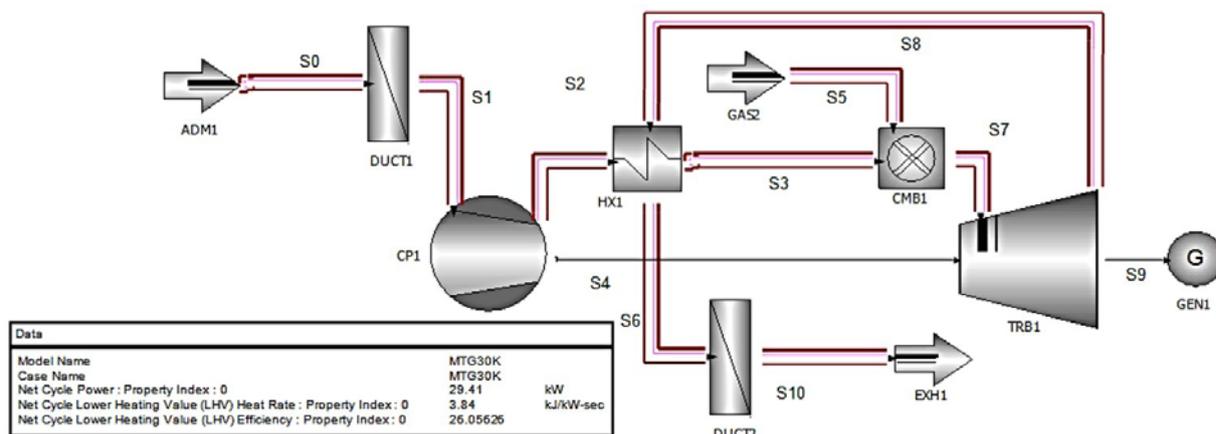


Figure 1. Schematic representations the model developed in GateCycle™

GateCycle™ software (GE Energy) was developed by Enter Software Inc., and is intended to assess performance at the design and off-design conditions of thermal systems and its components, such as: turbines, heat exchangers, compressor, etc. This software is based on the assessment of mass and energy flows of the plant components, in an integrated way, and using their specific performance curves, in order to satisfy Continuity equation and the First Law of Thermodynamics. GateCycle™ is also able to exchange data with MS-Excel™, through the Cycle Link add-in. Thus, data for all scenarios to be studied can be defined on MS-Excel worksheets (Gay et al., 2004).

The microturbine considered in this work is a Capstone microturbine, model 330, powered with diesel, with rated power of 30 kW and efficiency of 26% (ISO conditions: 15° C, 101.325 kPa, 60% RH) (Capstone, 2003). The microturbine model was developed considering component's performance data and fuel characteristic as detailed below, considering its operation at design point under ISO conditions.

- Compressor pressure ratio: 4.1 (Capstone, 2003);
- Air flow rate: 0.31 kg/s (Capstone, 2003);
- Fuel flow: 0.20 l/min (Capstone, 2003);
- Fuel (diesel) High Heating Value - HHV: 45144 kJ/kg (Capstone, 2003);
- Turbine rotational speed: 96000 rpm (Capstone, 2003);
- Radial compressor isentropic efficiency: 80% (Saravanamuttoo et al., 2009).
- Pressure losses: combustion chamber: 2.5%; admission and exhaust system: 1.2%; regenerator (cold and hot side): 2.0 (Malkamäki, 2015; Wilson, 2003).
- Combustion efficiency: 98% (Tan and Palanisamy, 2008).
- Turbine inlet temperature: 1120 K (Cafaro et al., 2009)
- Radial turbine isentropic efficiency: 82% (Saravanamuttoo et al., 2009).
- Regenerator effectivity: 85% [Wilson, 2003]
- Generator and AC/DC converter: 93.8% (Malkamäki, 2015).

Figure 1 also shows the main results obtained with the computational model developed. For design point, the power produced was 29.41 kW and the cycle efficiency was 26.06%. These values are very close to the ones reported by the manufactures, showing a relative error of 1.3% e 0.2%, for power and efficiency, respectively.

For turbine simulation operating at partial load (*off-design*), it was used internal GateCycle maps (performance curves) for determination of the compressor and turbine compartment. It was also considered that microturbine operates with variable rotational speed.

As stated above, the microturbine analyzed in this work is a Capstone microturbine with 30 kW capacity, powered with diesel. This turbine is installed in the Laboratory of Microturbines and Biomass Gasification of UNIFEI, in a fully instrumented experimental bench, from which it is possible do obtain a series of thermal and electrical parameters for different load conditions. Fig. 2 shows a schematic of the experimental bench with the indication of the different variables that can be measured.

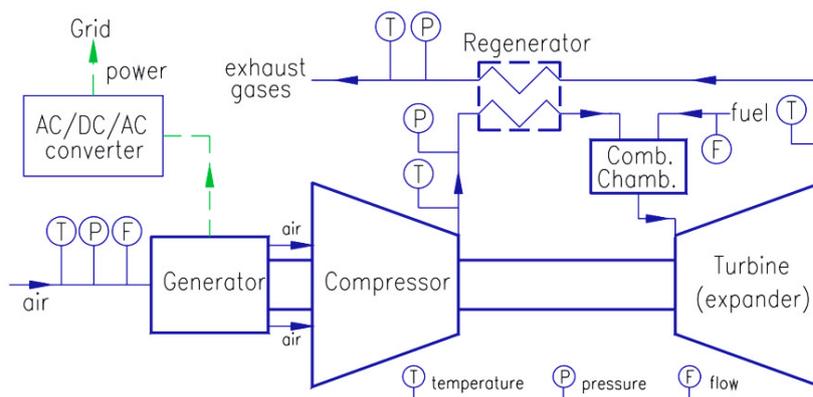


Figure 2.

7. RESULTS AND DISCUSSION

Initially it was conducted a preliminary characterization of fuels, in order to determine the main properties of interest for this work. Thus, it was determined the High Calorific Values (HHV) of the fuels used in this work by conducting experiments in an calorimeter IKA WORKS model C-2000 (Ika, 2003), except for biobutanol (BB), which LHV was obtained from (Pfromm, 2010). The following fuels were considered in this analysis:

- Diesel, purchased at gas stations in the region (DF).
- Biodiesel (BS100)
- A mixture containing 20% of biodiesel and 80% of diesel in volume (DS20DF80)

- A mixture containing 40% of biodiesel and 60% of diesel in volume (DS40DF60)
- A mixture containing 40% of biodiesel e 60% of sugarcane diesel in volume (DS40DF50)
- Sugarcane diesel (DC)

Table 1 shows HHV for the fuels mentioned above, as well as their density at 20 °C. The results shown represent the average values obtained for five samples. Fuels density were determined using a Sartorius analytical scale, model BL 210S wool (capacity of 210 g and a resolution of 0.1 mg), and a graduated pipette to measure volume.

Table 1. Fuels HHV and density.

Fuel	DF	DC	BS100	BC20DF80	BC40DF60	BB
HHV [kJ/kg]	44763	44860	40058	44152	43533	37334
Density [kg/m ³]	838	778	886	852	874	810

Fuels Lower Heating Value (LHV) were determined considering their typical composition (Giakoumis, E.G., 2013) and using Eq. (1) (Volpato et al., 2009).

$$\text{LHV} = \text{HHV} - 2440(9 \text{ H} + \text{W}) \quad (1)$$

Where: H hydrogen content of fuel (kg-H/kg-comb.)
W moisture content of fuel (kg-w/kg-comb.)

Initially the microturbine was started and was left running at idle, i.e., without load, for warming up. Then, the turbine was subjected to a series of loads, from zero to maximum load, which depends on the ambient conditions (temperature and pressure), in increments of 5 kW. For each applied load, it was waited until the microturbine reached steady-state operation to then initiate the measurements of the parameters indicated in Fig. 2. This procedure was repeated for each of the above listed fuels. The exhaust gases were also analyzed in order to determine its composition and to quantify pollutants presents, in this case are being considered the emissions of CO and total NO_x (NO + NO₂).

As state above, the comportment of any gas turbine is influenced by environmental conditions, so their performance should be expressed at standard ISO conditions (15° C and 101.325 kPa), in order to make feasible comparisons. The corrections parameters theta (θ) and delta (δ), which are shown o Eq. (2) and (3), respectively, should be applied to the experimental data, in a way that all parameters can be compared on the same basis (ASME, 1997).

$$\theta = \frac{T_1}{288,15 \text{ K}} \quad (2)$$

$$\delta = \frac{P_1}{101,325 \text{ kPa}} \quad (3)$$

Where: T₁ is the compressor admission temperature (ambient temperature),
P₁ is the compressor admission pressure (ambient pressure)

All other quantities of interest must then be corrected based on parameters theta (θ) and delta (δ), Thus, temperatures, pressures, mass and energy floes (power) are corrected according to Eq. (4), (5), (6) and (7), respectively (ASME, 1997). Therefore, in all figures presented below the values are normalized (ISO conditions).

$$T_{\text{cor}} = \frac{T}{\theta} \quad (4)$$

$$P_{\text{cor}} = \frac{P}{\delta} \quad (5)$$

$$\dot{m}_{\text{cor}} = \frac{\dot{m}\sqrt{\theta}}{\delta} \quad (6)$$

$$\dot{W}_{\text{cor}} = \frac{\dot{W}}{\delta\sqrt{\theta}} \quad (7)$$

Figure 3 shows a comparison of specific fuel consumption (sfc), which can be determined according to (Eq. 8), and turbine exhaust temperature, obtained through the computational model and from experiments performed in the Lab. of Microturbines Biomass Gasification of UNIFEI. As can be observed, both specific fuel consumption and exhaust temperature show good agreement, with maximum relative error of 1.10% and 0.93%, respectively, for maximum load condition. It is worth mentioning that the microturbine manufacturer specifies a exhausts temperature of 260 °C at design point (Capstone 2003), which is very close to the values obtained in this work (256,7 °C). Therefore, it is possible to conclude that the model developed can be used effectively to predict effectively the performance of the microturbine for different operational conditions.

$$sfc = \frac{m_f / \rho_c}{W_{LIQ}} \tag{8}$$

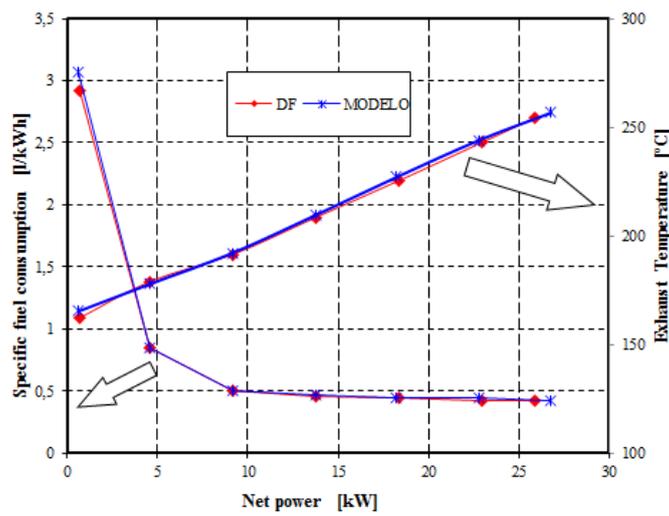


Figure 3. Exhaust temperature and sfc as a function of the net power produced.

In Figure 4 it is compared the microturbine behavior operating with conventional diesel (DF) and pure biodiesel (DS100), and the two biodiesel mixtures described above, I.E., DS20DF80 and DS40DF80. It can be observed that for a given microturbine rotational speed no significant variation of the net power produced is noticed. However, it should be mentioned that for each condition evaluated the parameter set is the power produced.

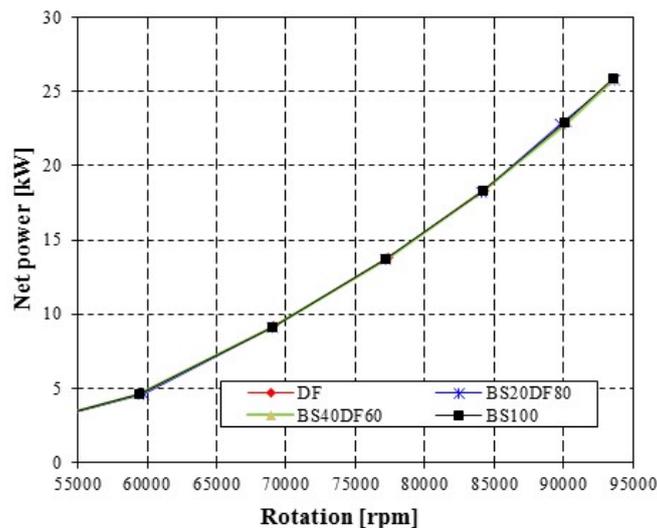


Figure 4. Net power as a function of the microturbine rotation

Figure 5 shows, for the same fuels and mixtures mentioned above, the specific fuel consumption, in l/kWh, as a function of the net power produced. It can be observed an increase in specific fuel consumption with the increase of the biodiesel content in the blend, for the whole range of the microturbine operation. When considering the pure biodiesel (BS100), the increase in specific fuel consumption is approximately 13.4% higher than the specific consumption with diesel, which occurs due to the lower heating value of the biodiesel.

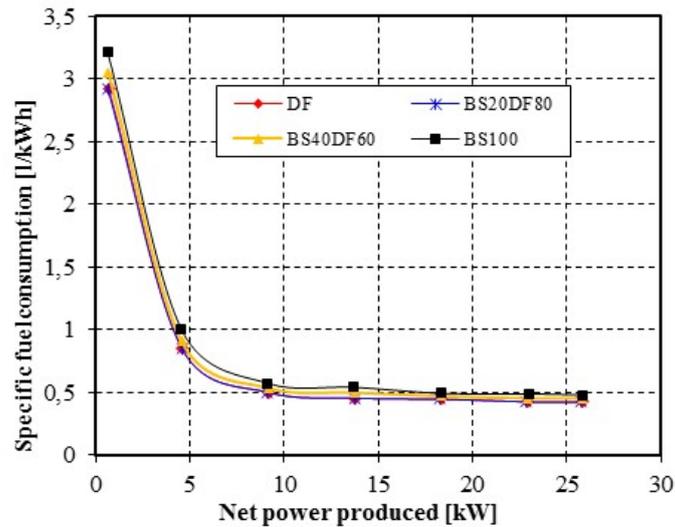


Figure 5. Specific fuel consumption as a function of the net power produced (DF, DS100, DS20DF80 and DS40DF80)

Figure 6 shows the specific fuel consumption, in l/kWh, as a function of the net power produced, for the conventional diesel (DF), sugarcane diesel (DC), and curves obtained through the computational model developed, for a mixture containing 50% of conventional diesel and 50% of sugarcane diesel (DC50DF50-Simul), and also for pure Butanol (BB-Simul). It can be observed very close results for specific fuel consumption at high loads (near the nominal) for all cases (experimental and simulation), except for butanol. When burning sugarcane biodiesel (DC) it was observed a reduction of 0.93% in specific consumption in relation to conventional diesel (DF). For low loads, this reduction in specific consumption reached 3.03%, however it is important to note that this reduction occurs for power around 0.75 kW, and this is not a condition where the microturbine will operate most of the time. Specific fuel consumption obtained with butanol higher than any other fuel shown in this figure, due to its lower heating value (33100 kJ/kg), when compared with the other fuels. It was observed an average increase of 26.4% in specific fuel consumption for butanol, in relation to conventional diesel.

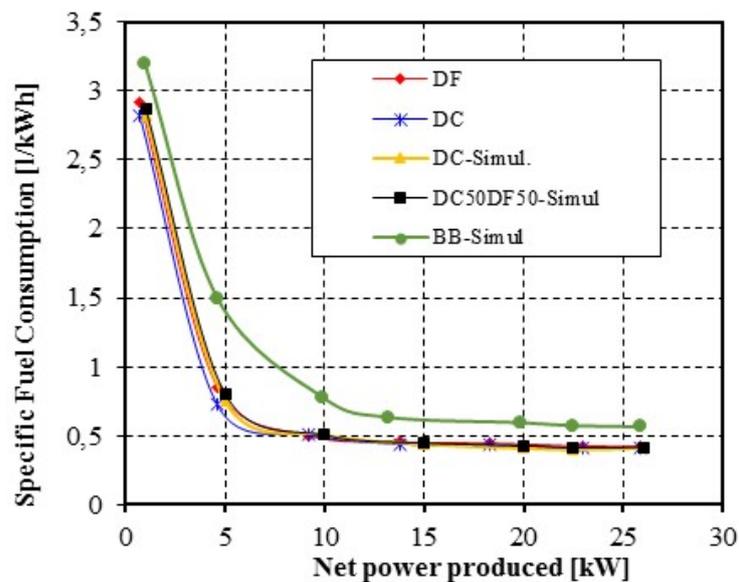


Figure 5. Specific fuel consumption as a function of the net power produced (DF, DC, DC50DF50, BB).

Figure 6 shows the thermal efficiency as a function the microturbine power, for conventional diesel (DF), sugarcane diesel (DC), mixture DC50DF50 and BB, which were obtained by the computational model developed. It can be observed that for all loads the efficiency is very close for all fuels, as were the specific consumption consumptions. At maximum load, BC presented an efficiency increase of 0.98% in relation to the DF. As expected, there was a reduction in efficiency for biobutanol, due to the same reason listed above, i.e., its lower heating value.

Figure 8a and 8b show CO and NOx (NO + NO₂) emissions, respectively, as a function of the turbine load, when burning conventional diesel (DF), biodiesel (BS100) and their mixtures (BS20DF80 and BS40DF60). With regard to

CO emissions, it is possible to notice that for all loads the use of biodiesel, pure or mixed with diesel, led to the increase in the emission of this pollutant. Incomplete combustion results in both CO and unburned hydrocarbons. CO emissions increase when there is insufficient residence time at high temperature.

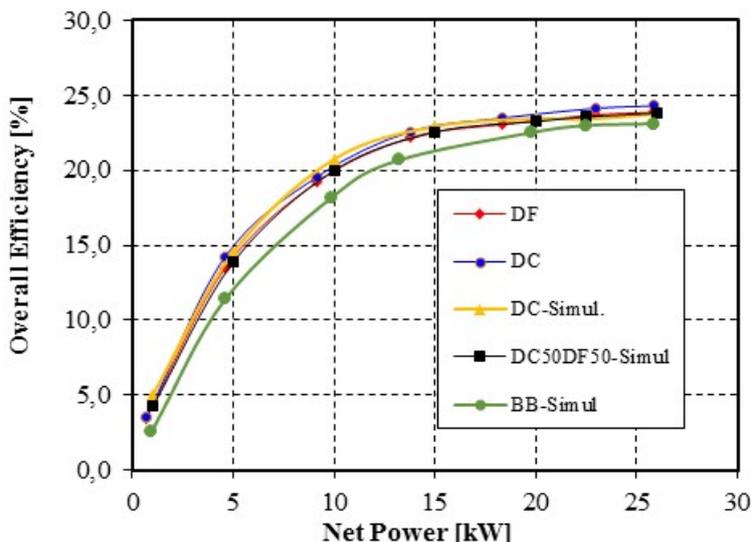


Figure 7. Overall efficiency as a function of the net power produced (DF, DC, DC50DF50, BB).

In relation to NO_x emissions, it can be observed in Fig. 8b an increase of the NO_x emissions with the load for all fuels, but a reduction of NO_x emissions with the increase of biodiesel in the mixture, for the same load. It must be considered that the formation of these compounds, in the case considered, is mainly a result of the oxidation of atmospheric nitrogen (N₂), due to the high temperatures in the combustion chamber. Beyond flame temperature, the kinetics of biodiesel combustion are faster as evidenced by the very clear plume which is an indication of shorter flames and residence time (Molière et al., 2007). This is in concordance with the higher CO emissions observed, as explained above.

As the fuel injectors were the same for conventional diesel and biodiesel, the lower richness in the primary zone due to the mere presence of oxygen in the molecule can decrease the rate of formation of prompt NO, that, in this case, represents only a small but non zero portion of total NO_x.

For low loads (lower than 8 kW) it possible to note an increase in NO_x emissions, which probably may be related to problems of fuel atomization in injector nozzle as low loads, however this behavior requires further studies. Finally, it should be noted that NO_x emissions for BS100 and mixtures (BS20DF80 and BS40DF60) were all smaller than emissions for DF, in all conditions. For all cases evaluated it was not detected SO_x and unburned hydrocarbons emissions.

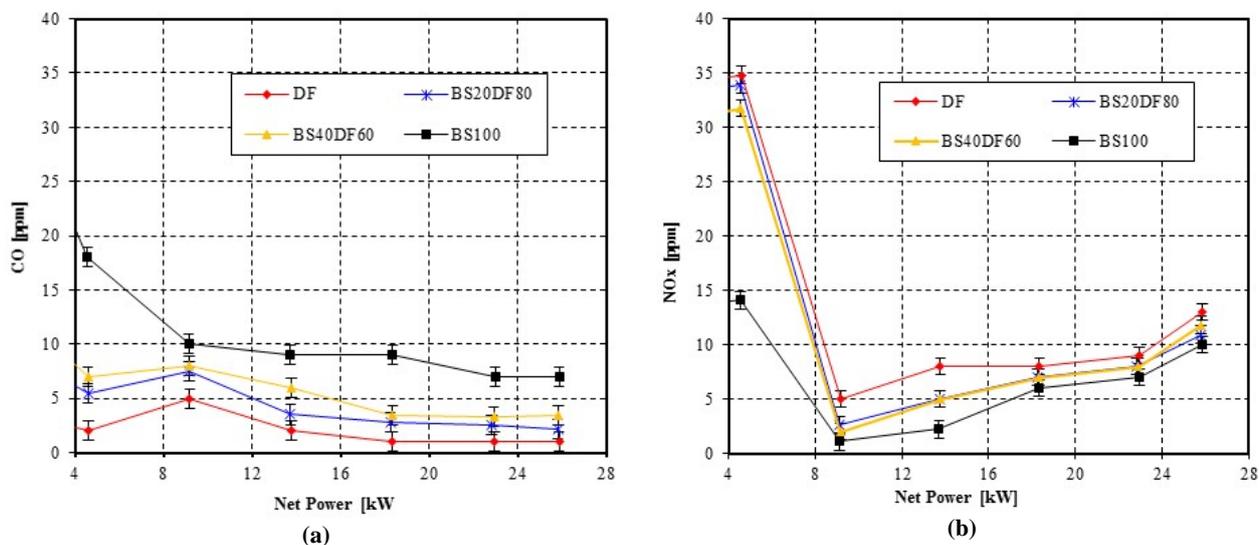


Figure 8. CO and NO_x emissions as function of the net power produced (DF, DS100, DS20DF80 and DS40DF80)

Unfortunately, it was not possible to assess the microturbine emissions when using sugarcane diesel (farnesane) and butanol, because during the realization of this work the microturbine fuel pump presented problems on power system (engine) and experiments with these fuels could not be finalized. Actions are being taken to replace this pump and in order to complete the experiments.

8. CONCLUSIONS

In this study, it was evaluated the performance of microturbine operating with conventional diesel, biodiesel, mixtures of conventional diesel and biodiesel, sugarcane diesel and biobutanol. Engine power generation, specific fuel consumption and, for some fuels, CO and NO_x emissions were determined. It was possible to observe only marginal reduction in specific fuel consumption for all fuels, except biobutanol, which demonstrated a higher specific fuel consumption and lower efficiency.

It was also observed that a higher content of biodiesel on mixtures resulted in higher CO emissions while NO_x emissions reduced. In addition, no significant power reduction were observed in all range of operations rotations of the microturbine.

This study demonstrates that a microturbine could be operated successfully with the fuels considered, which means that it could be utilized as prime movers in distributed and remote locations for power generation by burning renewable fuels.

9. ACKNOWLEDGEMENTS

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