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Mechanical Engineering

Crude palm oil as a complementary fuel for power generation in Amazonia: diesel engine performance, emissions, and economic assessment

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Abstract:

This paper evaluates internal combustion engine performance parameters (Specific Fuel Consumption and engine torque) and pollutant emissions (O., CO, and NO.), and also, provide an assessment of economic viability for operation in Amazonas state. Power supply to the communities in the Amazon region has as characteristics high costs for energy generation and low fare. Extractive activities include plenty of oily plant species, with potential use as biofuel for ICE (Diesel cycle) to obtain power generation together with pollutant emission reduction in comparison to fossil fuel. Experimental tests were carried out with five fuel blends (crude palm oil) and diesel, at constant angular speed (2,500 RPM – stationary regime), and four nominal engine loads (0%, 50%, 75%, and 100%) in a test bench dynamometer for an engine-driven generator for electrical-power, 4-Stroke internal combustion engine, Diesel cycle. Main conclusions are: a) SFC and torque are at the same order of magnitude for PO-00 (diesel) and PO-xx at $BHP_{50/75/100\%}$; b) O. emissions show consistent decreasing behavior as BHP increases, compatible to a rich air-fuel ratio ($\lambda > 1$) and, at the same BHP condition, O. (%) is slightly lower for higher PO-xx content; c) The CO emissions for PO-00 consistently decrease while the BHP increases, as for PO-xx those values present a non-linear behavior; at $BHP_{75\%\text{-}100\_loads}$, CO emissions are higher for PO-20 and PO-25 in comparison to PO-00; d) The overall trend for NO. emissions is to increase, the higher the BHP; In general, NO. emissions are lower for PO-xx in comparison to PO-00, except for PO-10 which presents slightly higher values than PO-00 for all BHP range; e) Assessment on-trend costs indicates that using palm oil blends for Diesel engine-driven generators in the Amazon region is economically feasible, with an appropriate recommendation for a rated power higher than 800 kW.

Keywords: renewable energy, biofuels, combustion, pollution, operational costs.

Introduction

Brazilian Amazonian region is known worldwide, and it is a sizeable territorial rainforest (~5.10^6 km²) in which the community's distribution is mostly sparse and with reduced population density (~3.4 inhabitants per km²). Most parts of its ~17 million inhabitants are far from the public electric power transmission grid. Thus, power supply to the communities in the Amazon, or isolated residents, is characterized by high costs

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for energy generation and low fare, due to the complexity in transportation logistics, low population density, and population low purchasing power. At this condition, the public subvention became mandatory to ensure the population´s access to electric energy.

Usually, Amazonian Energy Co. comprises distributed power plants operating with engine-driven generators rated within 40 kW up to 1,500 kW, using diesel oil, i.e., fossil fuel. A feasible way to supply the energy demand, in an environmentally friendly mode, is the utilization of oil-based alternative fuels to feed those power plants, i.e., biofuel as a renewable fuel. There are plenty of oleaginous plant species in the Amazon region, which presents high potential as biofuel for internal combustion engines (ICE) to obtain power generation.

A literature review indicates that using biodiesel blends in ICE, mostly obtain significant decreases in CO and total unburned hydrocarbon (HC) emissions (Damanik, Ong, Tong, Mahlia, & Silitonga, 2018), and also reduction of NO_X. An appealing option is to feed ICE with crude oils, typically in the Diesel cycle, i.e., compression ignition (CI). However, operational and maintenance difficulties may occur due to its fuel characteristics: high viscosity, poor fuel atomization, carbon deposits and the possibility of clogging the fuel lines (Ndayishimye & Tazerout, 2011; Almeida, Belchior, Nascimento, Vieira, & Fleury, 2002). There are some methods to reduce the crude oil viscosity, as: preheating (Bari, Lim, & Yu, 2002; Kalam & Masjuki, 2004; Delalibera, Campolina, Weirich Neto, & Ralisch, 2012), transesterification of various oils and fats (Kalam & Masjuki, 2002; Huzayyin, Bawady, Rady, & Dawood, 2004; Agarwal, 2007); Sharon, Ram, Fernando, Murali, & Muthusamy, 2013), blending with some primary alcohols (Sharon, Karuppasamy, Kumar, & Sundaresan, 2012) or diesel oil (Almeida et al., 2002; Yusaf, Yosif, & Elawad, 2011), and even combination of two of these methods (Ndayishimye & Tazerout, 2011). Direct injection (DI) engines are pointed out as better options for vegetal oil operation.

Preheating vegetal oils - and fuel blending - results in fuel injector life reduction in long-term tests (65°C – soybean oil; Delalibera et al., 2012) and increases in opacity (particulate matter emissions); when operating an ICE – Diesel cycle, in a real vehicle on the highway. Short-term tests indicate higher fuel consumption when submitted to any engine load condition in comparison to no-preheating (100°C – crambe, rapeseed, linseed, and jatropha oils; Delalibera et al., 2017); Power loss (intensified with preheating) and lower overall opacity also occurs in comparison to Diesel (fossil fuel), with best results for crambe and rapeseed. When preheating biodiesel blends, thermal efficiency improvements may not overcome energy losses, thus increasing SFC and decreasing engine torque output (Monteiro, Pianovski Jr., Velásquez, Rocha, & Bueno, 2013).

Benefits also include a reduction in pollutant emission achieved by using an environmentally friendly biofuel, in comparison to fossil fuel emissions. There are recent assessments on the CO_2 decline provided by biofuels production from palm oil in Brazilian Amazon (Cassol, Melo, Mendes, Fonseca, & Sanquetta, 2016), indicating that plantations in deforested areas could absorb around $5.3.10^6$ tons of $CO_{2\text{-Eq}}$; furthermore, reuse of the waste production could also increase the efficiency in CO_2 reduction.

This study aims to evaluate ICE performance parameters (SFC and engine torque) and pollutant emissions (O_2, CO, and NO_X). Experimental tests were carried out with five fuel blends (crude palm oil) and diesel, at constant angular speed (@2,500 RPM – stationary regime), and four nominal engine loads (0%, 50%, 75%, and 100%) in a test bench dynamometer, attached to an engine-driven generator for electrical-power, 4-Stroke internal combustion engine. Further on, assessment on the overall operation in Amazonas state (Brazil´s north region); including the economic viability of the palm oil blends in power-plant facilities (small-medium sizes).

Methodology

Biofuel blends samples characteristics

Five (5) fuel samples were considered for the engine tests, combining diesel oil (fossil fuel) and palm oil (renewable fuel), four different fuel blends and one for diesel oil, namely as "PO-xx" - where "xx" is the palm oil volumetric fraction (% v/v). Eight (8) combinations have their properties determined preliminarily: PO-00 (100% diesel oil), PO-05, PO-10, PO-15, PO-20, PO-25, PO-30, and PO-100 (100% palm oil). Samples preparation was under reference standards (ANP, 2011), and it is already blended when it occurs fuel injection inside the ICE.

The African Palm (Elaeis guineensis) is native to Africa and known in Brazil as oil palm ("dendezeiro"), it is a long cycle or perennial cultivation, and it is well adapted to the climate in Brazil´s north region; its oil productivity reaches 4,000-6,000 kg ha^{-1} $year^{-1}$ - The highest among oilseed species (Gonzalez, 2008). Figure 1 shows images for the palm tree, biodiesel production, crude palm oil, and fruit ("dendê"). Oil extraction from the mesocarp (pulp) produces palm oil, from the endocarp produces the palm kernel oil.

Figure 1.
Palm tree ("dendezeiro"), Biodiesel production from palm oil, and Crude palm oil. (Gonzalez, 2008; Levitt (2017).

Fluid properties are key factors to ICE performance, mainly: High Heating Value (HHV, MJ kg^{-1}), density (ρ, kg m^{-3}) and Cetane Number (CN, non-dimensional). HHV is the amount of chemical energy contained in the fuel; in this work, it was measured according to standard procedure (ASTM, 2013). As reference values, HHV, ρ and Tf (flash point) for diesel oil (PO-00) are, respectively: ~45.0 MJ kg^{-1}, 850-900 kg m^{-3} at 100°C (Brunetti, 2012; ANP, 2011); while for crude palm oil, respectively: ~37.0 MJ kg^{-1}, 911.8 kg m^{-3} at 25°C (Neto, Rossi, Zagonel, & Ramos, 2000) or ~39.5 MJ kg^{-1}, 910.0 kg m^{-3} at 20°C (Gonzalez, 2008). For physical-chemical characterization (fuel oils), density and CN, the following standards apply, respectively: D396, D4052, and D613 (ASTM, 2018a; 2018b; 2018c; 2016.

Measurements for fuel blend density ($\rho_{PO\text{-}xx}$), $HHV_{PO\text{-}xx}$ and other fluid properties were obtained by using a density meter (PARR, DMA 4500), bomb calorimeter (PARR, model 1341), with detailed methodology available in Souza et al. (2009); Table 1 provides main properties for fuel samples. Density increases linearly with the addition of PO (% v/v) in the fuel blend, while HHV and CN decrease. Also, fuel miscibility was provided by shaking the fuel blends samples, before fueling the ICE for tests; once density differences also imply in two-phase separation (when storage occurs), with diesel oil at the top and palm oil at the bottom.

TABLE 1.
Biofuel blends main characteristics.

Code	PO, v/v (%)	ρ (kg m^{-3})	HHV (MJ kg^{-1})	CN (calculated)
PO-00	0	854.0	45.65	47.7
PO-05	5	856.3	45.26	48.0
PO-10	10	859.1	44.24	46.8
PO-15	15	862.4	44.19	47.3
PO-20	20	865.4	43.58	45.4
PO-25	25	868.0	42.61	---
PO-30	30	873.0	41.96	---
PO-100	100	918.9	38.21	---

Liquid fuel circulation and injection systems are strongly affected by its density. Once the fuel system is designed to operate within a range of fuel properties (based on volume flow), it is expected low fuel mass flow injected in the combustion chamber (inside piston-cylinder) for higher densities ($\rho_{Palm\text{-}Oil}$ ~7.5% higher than ρDiesel-Oil - see Table 1). Thus, resulting in lower engine torque (at constant speed), intensified by the effect of lowering HHV as much palm oil is in the fuel blend.

As for CN, it is a parameter applied to ICE - CI types, analogous to Octane Number (ON) in SI - Spark Ignition types (Brunetti, 2012). It compares test fuel ignition delay to a reference fuel and defines the time elapsed between injection start and the first identifiable pressure increase during the combustion stroke. Engine manufacturers in the USA recommend 40 < CN < 50, while reference standards (ABNT, 2016; ANP, 2011) indicate $CN_{minimum}$ = 42 for diesel oils - S500 and S1800 - when the product does not contain CN improver additive. PO inclusion in fuel blends samples promotes a decreasing bias, reaching this lower limit at PO-25; even though the $CN_{PO\text{-}25}$ and $CN_{PO\text{-}30}$ are not pointed out in Table 1, it is expected lower values in comparison to other fuel blends when using the four-variable equation for cetane index calculation according to normative (ASTM, 2018c; ABNT, 2016). The higher the CN, the better the combustion is expected. Nevertheless, very high or very low CN may cause ICE operational troubles; respectively, advances in combustion (↑ CN) or incomplete combustion and smoke emission (↓ CN) – when ignition occurs before air and fuel are adequately proper (Bunetti, 2012). Low values also induce engine to fail, causing vibration, excessive increase of air temperature, delay in engine warming and, finally, decreases in combustion efficiency. Furthermore, low CN values also imply in cold start, since CN indicates the readiness of the fuel in auto-ignite at a specified pressure and temperature.

Vegetal oils when used as fuel in CI engines (pure or blends), generally result in incomplete combustion due to its different fluid properties when compared to diesel (Brunetti, 2012): lower CN and higher molecular weight, viscosity and surface tension. Practical problems include (Brunetti, 2012): cold start difficulty, carbon deposits formed in the injector nozzles (requires more frequent cleaning) and cylinders (heat exchange reduction and increases unburned hydrocarbons at exhaust gases), lubrication channels clogging, and filters and lubricant oil contamination. Lower viscosity can be obtained when heating palm oil to 100°C, avoiding poor atomization, and cylinder head deposits at acceptable levels similar to diesel oil operation (Almeida et al., 2002).

Experimental setup and measurement instruments

ICE for experimental tests in the present work is a stationary model (Cummins 4B-3.9, naturally aspirated - electrical power supply), diesel cycle (CI type). It is a 4-Stroke, 4-cylinders, 2,500 RPM as maximum angular speed and 850 RPM as rated speed, while maximum power is 56.6 kW (76 HP). The ratings of the engine are in conformance with requirements specified in technical standards (ABNT, 1995; BSI, 1992; DIN, 1991). Table 2 provides the ICE main characteristics.

TABLE 2.
General data for test ICE.

Specification	Cummins 4B-3.9
Number of cylinders	4 (in line)#
Fuel system (Air/Fuel control)	Naturally aspirated
Ignition system	Compression-Ignition (CI), Mechanical/Bosh
Displacement volume, c.c. [cm³]	3920
Bore, cylinder diameter [mm]	102.1 (or 4.02")
Stroke, piston length [mm]	119.9 (or 4.72")
Oil system capacity [cm³]	10.9
Wet weight [kg]	338-355
Maximum speed (RPM)	2,500
Compression ratio	18.5:1
Maximum torque (N.m@RPM)	469-506
Maximum Power (kW@RPM)	56.6 kW@2,500 RPM#

The engine connects to a hydraulic PTX dynamometer (model Power Test 50X01), where braking force is modified, according to load input required for experimental test conditions. The test bench can provide 372.85 kW (or 500 HP) at 1,600 RPM, while minimum BHP is 5.96 kW (or 8 HP), see Figure 2.

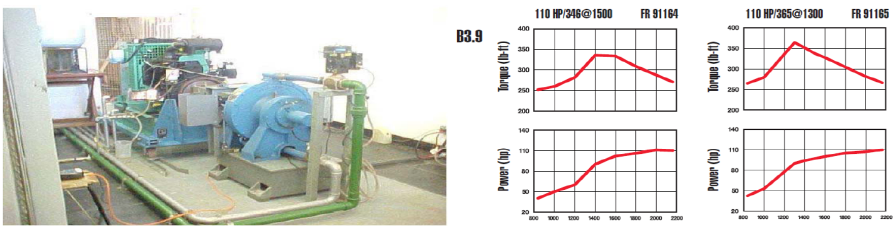

FIGURE 2.
Experimental apparatus (setup and dynamometer bench test) for Diesel engine and characteristic curves from the manufacturer (Cummins, 2018).

An LT commander software controls the engine/dynamometer, allowing to monitor of engine torque and power (T_{Shaft}, N.m; P_{Shaft}, kW). Fuel mass flow (m_{Fuel}, g s^{-1}) measurements are performed by a flowmeter (Model: Flowmate Oval MIII – 1 mL/pulse and ± 1% RD accuracy for models 40/41/45); a return circuit is assembled to assure the actual flow measurement. Exhaust gas emissions were registered by a flue gas analyzer (Gastec, model: Ecoline 6000), with technical specifications given in Table 3.

TABLE 3.
Portable flue gas analyzer - technical data and specifications.

Emission gas (parameter)	Range	Resolution	Accuracy	Measuring device (Sensor)
O_2	0 - 25%	0.1%	± 0.1% vol	Eletrochemical
CO	0 - 10,000 ppm	1 ppm	± 2% (up to 2,000 ppm)	Eletrochemical
NO_x	0 - 6,000 ppm	1 ppm	---	Calculated

Experimental tests procedures

Performance tests for ICE, including fuel consumption (by volumetric methods), are following technical standards. The flue gas analyzer probe is positioned at the exhaust pipe to collect the emissions parameters data. Engine softening cycle was applied (Table 4), and after finishing that run, each experimental test began. All engine tests started operating with PO-00, to latter on performance comparison to PO-10/20/25 results; PO-30 and PO-100 were not considered for engine tests due to their fluid properties (see Table 1), while

PO-05 was considered for economic assessment and PO-15 had results limited to torque and SFC (not presented in this work). For each fuel blend operation, the engine runs took two hours (2h) at constant rated speed (2,500 RPM). The following nominal engine loads were applied: 0% (8 HP or ~6 kW at the test bench), 50% (38 HP or ~28 kW), 75% (57 HP or ~42 kW), and 100% (76 HP or ~56.6 kW).

TABLE 4.
Softening cycle.

Time (minutes)	Nominal angular speed (RPM)	Load or Brake Horse Power (BHP)
0-4	850	~1.5 kW (~2.00 HP)
4-8	1,500	~3.0 kW (~4.00 HP)
> 8	2,500	~9.6 kW (~13.00 HP)

Specific fuel consumption (SFC, g kW^{-1} s^{-1}) is provided by Equation (1), where: m_{Fuel} (g s^{-1}) is the fuel mass flow, $P_{Shaft\text{-}BHP}$ (kW) is the engine shaft power. Equation (2) is the SFC uncertainty calculation.

$$SFC\ (g.kW^{-1}.s^{-1}) = m_{Fuel} \cdot (P_{Shaft\text{-}BHP})^{-1} \quad (1)$$

$$u_{SFC} = \left(\left(m_{Fuel} \cdot (P_{shaft})^{-2} \right) + \left((P_{shaft\text{-}BHP})^{-1} \right) \right)^{0.5} \quad (2)$$

Economic assessment

The cost of replacing diesel turns the new charge of energy generation a function of the prices of diesel and palm oil and the expenses for maintenance. Maintenance costs for the operation of an engine-driven generator with rated power within 40 kW and 100 kW for operation with diesel oil (PO-00) and pure palm oil (PO-100) considers, respectively, ~0.34 US$ h^{-1} and ~2.36 US$ h^{-1} (Soares, Vieira, & Nascimento, 2003); when evaluating a 60 kW / 76 kWA engine-driven generator using an MWM Engine (Model D 229-6, 90 HP at 1,800 RPM). Their maintenance costs include spare parts and service, considering: (a) Each 400h cycle, Cleaning of injector fuel and pump, with partial decarbonization of the combustion chambers; (b) Each 800h cycle, Exchange of injector fuel and pump, and other spare parts, with full decarbonization of the combustion chambers. Those maintenance costs include lubricant and filter replacement and depend upon operation time; thus, the more electrical energy is generated, the lower the expenses are.

Assuming that in operation with fuel blends will afford a Mean Time Between Maintenance (MTBM) values within those presented for PO-00 and PO-100, electrical energy for operation with their blends will be higher than that for PO-100. Then for the engine-driven generator considered in this work, the maintenance expenses would be computed, respectively for PO-00 and PO-100, as 55 US$ MW^{-1} h^{-1} (= 0.34 US$ h^{-1}/0.0425 MW) and 8 US$ MW^{-1} h^{-1} (= 2.36 US$ h^{-1}/0.0425 MW). Charges for fuel were computed as follows: 633 US$ ton^{-1} ($\rho_{PO\text{-}100}$) and 0.43 US$ ton-1 (ρPO-00). Thus the expenditures values for energy generation result in ~135.66 US$ MWh^{-1} (diesel) and ~193.00 US$ MWh^{-1} (PO-25); actually, those values fluctuated 184.93-193.97 US$ MWh^{-1} for the blends assessed in this work (PO-10, PO-15, PO-20, PO-25).

A database was provided by Amazonian Energy Co. for a typical monthly (2004, June) as ~52,200,981 kW h^{-1} as energy demand, which corresponds to a monthly diesel amount of ~15,495,460 liters. Thermal generation facilities comprise 92 small power plants that operate 386 engine-driven generators (2004 data basis), of which 132 are manufactured by Cummins, with rated power ranging from 40-1,500 kW (Soares et al., 2003).

Results and discussion

Experimental results for measured SFC (g kW^{-1} s^{-1}) and torque (N m^{-1}), at different BHP (dynamometer load) and constant engine speed (2,500 RPM), are indicated in Figure 3. For BHP0%_load ($BHP_{Nominal}$ ~6 kW at the test bench), dynamometer indication presents a significant range variation (6.6 kW < BHP < 11.3 kW); thus, when comparing $SFC_{minimum}$, at that condition it needs a careful assessment for addressing conclusions. At BHP0%_load (BHP_{Nomina}l ~6 kW), PO-10 presents the lowest SFC and the highest torque ($SFC_{minimum}$ ~0.520 g kW^{-1} s^{-1}; $T_{maximum}$ ~48 N m^{-1}), while when operating with PO-00 it shows $SFC_{maximum}$ ~0.850 g kW^{-1} s^{-1}. When loads are applied at the dynamometer ($BHP_{50\%/75/100\%\_loads}$), no remarkable changes occur in SFC, as it happens for $BHP_{0\%\_load}$. HHV, ρ and μ (absolute viscosity, Pa.s) are key factors on engine fuel consumption; palm oil biodiesel can present an HHV ~14% lower and kinematic viscosity ($\upsilon = \mu \rho^{-1}$) four times the ones for diesel fuel, thus resulting in 10% higher fuel consumption (Sharon et al., 2012).

As BHP increases, SFC shows non-linear decreases while torque increases almost linearly, for all fuel blends under test; consistent to literature results for ICE characteristic curves (Brunetti, 2012). Additionally, low SFC is desirable, once it implies the highest engine efficiency (↑ η, %). At $BHP_{0\%\_load}$ - low engine power is available - there are SFC increases for higher crude palm oil content in the fuel blend; it's a consequence of energy content lowering (↓ HHV_{blend}) and higher density (↑ ρ_{blend}). In fact, as pointed out previously (Table 1), fluid characteristics indicates ρminimum,PO-00 (854 kg m^{-3}) and $HHV_{maximum,PO-00}$ (45.65 MJ kg^{-1}), resulting in fuel consumption higher for any other fuel blend than PO-00, no matter the BHP condition; in other words, fuel mass flow (m_{Fuel}, g s^{-1}) raises when BHP is intensified.

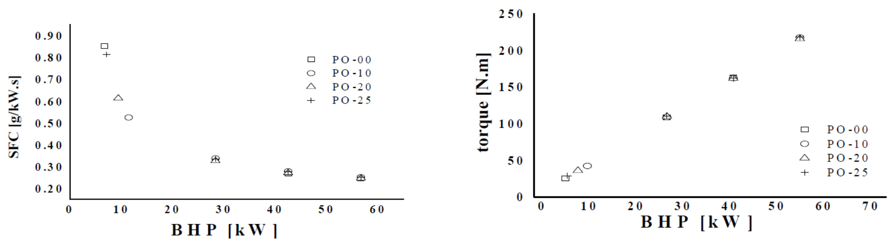

FIGURE 3.
SFC and Torque versus BHP – engine at constant angular speed (2,500 rpm).

Still in Figure 3, at $BHP_{100\%\_load}$ (56.6 kW@2,500 RPM), $SFC_{PO\text{-}00\ \&\ PO\text{-}blends}$ ~0.250 g kW^{-1} s^{-1} and $T_{PO\text{-}00\ \&\ PO\text{-}blends}$ ~220 N m-1, .i.e., there are no significant changes in SFC when palm oil is blended to diesel. A similar ICE model (Cummins 4BTA-3.9) operating on fuel blends (soybean origin biodiesel) obtained maximum power at 2,467 RPM, respectively: $SFC_{Diesel\text{-}100\%}$ ~0.098 g kW^{-1} s^{-1} (or 352.8 g kW^{-1} h^{-1}) / $SFC_{Biodiesel\text{-}100\%}$ ~0.102 g kW^{-1} s^{-1} (or 368.6 g kW^{-1} h^{-1}), and $T_{Diesel\text{-}100\%}$ ~175 N m^{-1} / $T_{Biodiesel\text{-}100\%}$ ~169 N m^{-1} (Castellanelli, Souza, Silva, & Kailler, 2008). Those authors also report that, B-20 fuel samples (20% v/v) present a better performance when comparing to B-00 (100% Diesel) for all parameters evaluated, i.e., SFC, torque and power; while higher biodiesel contents (50%, 75%, and 100%) presented worse performance in comparison to B-00. Engine thermal efficiency usually increases - reduction in thermal losses and exhaust gases remaining energy, when using biodiesel fuel blends between 10-20% (Monteiro et al., 2013; Bueno, Velásquez, & Milanez, 2011; Castellanelli et al., 2008). Literature results - for castor oil blends - indicate that SFC is mainly governed by fuel density and engine thermal efficiency increases, and decreases in HHV (Bueno, Velásquez, & Milanez, 2011).

Figure 4 shows experimental results for pollutant emissions, respectively, O_2, CO, and NOX. Firstly it is observed that O_2 (%) varies from a maximum value around 17% down to around 13%, with consistent decreasing behavior as BHP increases; those values are compatible with a rich air-fuel ratio ($\lambda > 1$). At the same BHP condition, O_2 (%) is slightly lower for higher PO-xx content, with smaller differences at $BHP_{100\%\_load}$ (#13%). Theory for ICE Diesel cycle indicates that a good combustion process occurs when there is excess air (Brunetti, 2012); at optimum conditions, all of the O_2 that gets inside the combustion chamber reacts with the fuel to obtain thermal energy, so a small excess of air is provided to ensure this will. As flue gases at exhaust pipe present a high concentration of O_2, results indicate combustion completeness (Figure 4 - O_2 results).

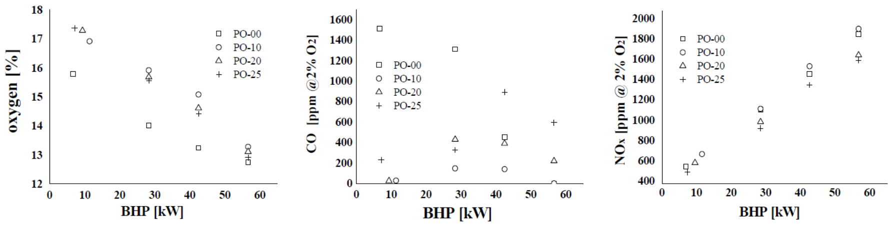

FIGURE 4.
Emissions (O_2, CO, and NO_X) - engine at constant angular speed (2,500 RPM).

The CO emissions for PO-00 (diesel) consistently decrease the higher the BHP is; whereas for crude palm oil fuel blends (PO-xx) those values present a non-linear behavior (parabolic) - close to zero at $BHP_{0\%\_load}$, maximum values at $BHP_{50\text{-}75\%\_loads}$, and lowering again at $BHP_{100\%\_load}$. In comparison to PO-00, CO emissions are higher for PO-20 and PO-25 at $BHP_{75\%\text{-}100\_loads}$; trends like that ones cannot be generalized and must be interpreted with caution, as pointed out in the existing literature (Damanik et al., 2018). Efficiency loss occurs at $BHP_{75\%/100\%\_loads}$, probably due to injection pressure loss that leads to inefficiency in the fuel atomization process - higher density ($\rho_{PO\text{-}xx}$) can induce longer vaporization time. Literature reports CO emissions decreasing at $BHP_{50\%\text{-}75\%\_loads}$ for PO-100 in a 70 kW diesel-generator engine (Almeida et al., 2002). The CO emissions occur due to incomplete fuel combustion (Damanik et al., 2018; Brunetti, 2012), that is when the fuel flame temperature cools down, and the progression to CO_2 is not complete. Also, when $\lambda > 1$ (rich air-fuel ratio), typically in the ICE Diesel cycle, CO emissions occur instead of CO_2, once there is insufficient O_2 to complete combustion (Kalam & Masjuki, 2004). To promote complete combustion oxygenated fuel can be used, as occurs to palm oil, which presents high O_2 content in its molecular composition (Baskar & Senthilkumar, 2016; Sanjid et al., 2014).

Regarding NO_X emissions, it corresponds to NO (~90%) and NO_2 (~10%), mainly generated by nitrogen from fuel and the air (thermal – temperature dependent; and prompt – flame front region), i.e., Zeldovich mechanism strongly dependents on flame temperature (Brunetti, 2012). The gas analyzer collects data in NO_2, however once released into the atmosphere, NO rapidly becomes NO_2. Thus, NO_X emissions (ppm @2% O2, see Figure 4 - NO_x results) behavior consistently increases as high the BHP is with an overall tendency in increasing NO_X, reaching 1600-1900 (ppm @2% O_2) for all fuel blends at $BHP_{100\%\_load}$. It is consistent with the combustion chamber temperature increases when BHP increases, thus providing growth in NO_x emissions; Zeldovich equations have their effect intensified for T > 2000 K. Higher NO_X emissions occur for oxygenated biodiesel, in comparison to diesel (Debnath, Sahoo, & Saha, 2013); engine tests on PO-100 (70 kW diesel-generator engine) indicates lower values for NO_X emissions in all BPH conditions (Almeida et al., 2002). Also, the flame temperature is related to the fuel HHV, then considering that fuel blends (PO-xx) have lower HHV in comparison to PO-00 (diesel oil), NO_x emissions are lower for PO-xx. Experimental results obtained in this study confirm those trends (Figure 4 - right side), except for PO-10, which presents slightly higher values than PO-00 for all BHP range.

Table 5 presents the monthly fuel demand for electrical power supply, off-grid in Amazon state (Brazil ́s north region), to provide an assessment on the technical and economic feasibility of crude palm oil as diesel complement in Amazonas state. In local thermal power plants, monthly diesel demand corresponds to $SFC_{average}$ ~0.297 g kW^{-1} s^{-1}, which is close to $SFC_{PBHPO\text{-}00\ \&\ PO\text{-}blends}$ at $BHP_{75\%\_load}$ (see Figure 3). Assuming the $SFC_{average}$ ~0.297 g kW^{-1} s^{-1}, it is possible to infer the volume demand for palm oil, for fuel blends combination (PO-xx) to supply monthly energy demand in the Amazon state.

TABLE 5.
Biofuel and fuel monthly demand for electrical power generation in the Amazon state.

Biofuel blend	Palm Oil ($m^3.10^{-3}$)	Diesel oil ($m^3.10^{-3}$ or liters)
PO-00	---	15,495,460
PO-05	774,923	14,723,537
PO-10	1,549,846	13,948,614
PO-15	2,324,769	13,173,691
PO-20	3,099,692	12,398,768
PO-25	3,874,615	11,623,845

Figure 5 indicates trend costs for electrical generation. Its behavior is slightly logarithmic and tends to be asymptotic at ~191 US$ MWh^{-1}. Generation cost by rated power (Figure 5, right side), is obtained by interpolating reference data (Amazonian Energy Co.); it indicates that although the operating diesel-generators with biofuel is economically feasible (< 191 US$ MWh^{-1}), the maintenance cost effect is more pronounced for a rated power higher than 800 kW.

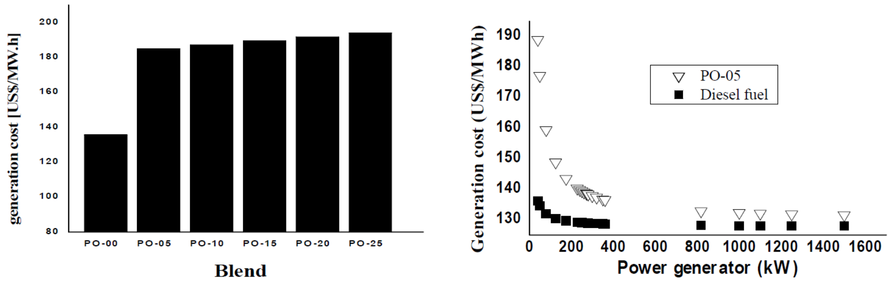

FIGURE 5.
Trend costs for electrical generation and costs by rated power (PO-05).

Besides the environmental issue, palm oil produced in the Amazonian villages tends to be cheaper due to logistic reasons, and may also create a source of income for the local population and stimulate mechanism for people fixation on those places. The use of palm oil as an additive, or as supplement diesel oil may contribute to the strengthening of the regional economy and reduce diesel oil demand in the Amazonian region.

The economic feasibility of processing of palm oil for biofuel production on the Amazon is highlighted by the fact that most of the electricity used in the region be from diesel oil and petrol; the cost of transporting the fuel for more remote locations can reach three times the value of the fuel itself (Gonzalez, 2008). The extent to which the engine performance and exhaust emission parameters increase or decrease depends on the type (vegetal or animal origin) and volume fraction in blends, as pointed out in the existing literature (Damanik et al., 2018).

As final comments, no preheating was required once fuel blends under tests present physical-chemical properties in the commercial range (ANP, 2011). Furthermore, economic feasibility demonstrates the potential for using those palm oil blends as a complement or substitute for diesel oil in small power generation in the Amazonian region.

Conclusion

Main conclusions are: a) SFC and torque are at the same order of magnitude for PO-00 (diesel) and PO-xx at $BHP_{50/75/100\%}$; b) O_2 emissions show consistent decreasing behavior as BHP increases, compatible to a rich air-fuel ratio ($\lambda > 1$) and, at the same BHP condition, O_2 (%) is slightly lower for higher PO-xx content; c) The CO emissions for PO-00 (diesel) consistently decrease as high the BHP is, while for crude palm oil fuel blends (PO-xx) those values present a non-linear behavior (parabolic); at $BHP_{75\%\text{-}100\_loads}$, CO emissions are higher for PO-20 and PO-25 in comparison to PO-00; d) NO_X emissions (ppm @2% O_2, see Figure 4 - NO_x results) have an overall tendency in increasing, as high the BHP is, reaching 1600-1900 (ppm @2% O_2) for all fuel blends at $BHP_{100\%\_load}$; In general, NOx emissions are lower for PO-xx in comparison to PO-00, except for PO-10 which presents slightly higher values than PO-00 for all BHP range; e) Assessment on trend costs for the electrical generation (including maintenance) indicates that using palm oil blends for Diesel engine-driven generators in Amazon region is economically feasible (< 191 US$ MWh^{-1}), and even more interesting for a rated power higher than 800 kW.

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