ENERGY AND EXERGY ANALYSIS OF A CENTRIFUGAL PUMP DRIVEN BY A DIESEL ENGINE POWERED WITH TERNARY MIXTURE OF DIESEL, BIODIESEL AND ANHYDROUS ALCOHOL.

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Abstract. *Fossil fuels depletion and the stringent restrictions on atmospherics emissions has led to the rational use of natural resources and the application of renewable fuels. Biodiesel is a renewable and biodegradable alternative fuel that does not requires changes in internal combustion engines, providing lower carbon monoxide emission rates, but with a higher NOx emission rate compared to diesel fuel, thereby creating an opportunity to use ternary mixtures of diesel, biodiesel and other compounds for the minimization of this pollutant. The exergy analysis is an appropriate tool for energy resources optimization because it takes into account the mass balance, the First Law of Thermodynamics, and the Second Law of Thermodynamics, quantifying the potential use of energy resources. The exergy analysis locates waste and loss in thermal systems, directing efforts to reduce inefficiency in the processes. By using energy and exergy analisys this study evaluates the operation of a centrifugal pump driven by a single cylinder Diesel engine fueled with mineral diesel and a ternary mixture composed of mineral diesel (85%), biodiesel (10%) produced from waste cooking oil (WCO) and anhydrous alcohol (5%). The energetic and exergetic efficiencies are presented. Also the rate of exergy destroyed in the engine is presented and considerations in order to minimize this are discussed.*

Keywords*: Biodiesel, Exergy, Diesel engines.*

1. INTRODUCTION

The interest in renewable energy has grown extensively in recent years primarily driven by factors such as the imminent exhaustion of natural reserves of fossil fuels, the vulnerability in the supply of such concentrated energy source in countries with economic and political instability and the increasingly stringent emissions regulations from combustion processes.

Bio-fuels, such as alcohol and biodiesel have been widely proposed as alternative fuels for combustion engines by compression (Diesel cycle). This interest in the use of such fuels is due to several factors, such as reducing the dependence on imported oil, creating a market for excess production of vegetable oils and animal fats, the use of renewable and biodegradable fuel, reducing global warming due to closed carbon cycle by recycling CO_2, increasing potential for lubrication and reduction of carbon monoxide exhaust emissions, unburned hydrocarbons and particulate matter emissions from engines (Ribeiro *et al*, 2007).

1.1. Biodiesel

Biodiesel (fatty acids alkyl esters) is an alternative fuel derived from the reaction of vegetable oils or animal fats and alcohol with or without a catalyst. It is biodegradable, nontoxic and can significantly reduce the rates of toxic gas emissions that contribute to greenhouse gases during the combustion process in engines (Di *et al*, 2009).

One of the methods used for biodiesel production is the transesterification that converts fat acids to an ester (biodiesel). The transesterification thus refers to a reaction between a triglyceride and an alcohol (methanol, for example) to form an ester (methyl ester, for example).

With transesterification it is possible to obtain a fuel (biodiesel) with lower viscosity than vegetable oil. Biodiesel has, on average, a higher viscosity than mineral diesel. Candeia et al (2009) in their studies, found that biodiesel from soybean oil or methyl ethyl showed viscosity between 4 and 5 mm^2/s and higher, compared to that of fossil diesel ($3mm^2/s$).

1.2. Biodiesel Effects on Combustion Engine Performance

Biodiesel can be used in Diesel engines with little or no constructive amendment. Though the applications of vegetable oils have been intensified since the 1950s, researches were needed on the design, engine technology and fuel, leading to the conclusion that the thermal efficiency of vegetable oil biodiesel is close to or even superior to fossil diesel. Their average toxic gas emissions rates are lower than mineral diesel, although some studies have shown more accumulation of deposits in engine internal walls (Cetinkaya *et al*, 2005).

1.2.1. Effective Power Curve

Several researchers studied engine effective power when using biodiesel compared to mineral diesel. Kaplan et al. (2006) compared sunflower oil, diesel and biodiesel in full or partial loads at different speeds in an engine with a power of 53 kW and 2.5 L. A loss of torque and power at full load of 5% to 10% was obtained at low speeds to high speeds, respectively.

Lin *et al*. (2007) tested mixtures of ULS diesel (ultra low sulfur diesel) and biodiesel from palm oil in an engine of 2.84 L, naturally aspirated. The loss of power at full load was only 3.5% with pure biodiesel and 1% with blend B-20.

According to Çetinkaya *et al* (2005), when using biodiesel fuel the power is approximately the same as that obtained when using mineral diesel when it comes to vehicle engines. In their experiments in a Renault Megane vehicle with a four-stroke, four-cylinder engine in road tests of 7500 km to investigate the performance with the use of biodiesel from waste cooking oil, a small reduction of the engine effective power was found. In general, the reduction in power with the use of biodiesel is justified by the lower heating value of biodiesel compared to mineral fuel.

1.2.2. Brake-Specific Fuel Consumption

The brake-specific fuel consumption (BSFC) is the ratio of fuel mass consumption and the energy expended by the engine. It is expected to increase about 14% with the use of biodiesel compared to diesel fuel, corresponding to the reduction of lower heating value of biodiesel on a mass basis. In other words, the lower heating value of biodiesel should be compensated with a higher fuel consumption (Lapuerta *et al*, 2008). Most studies confirm that fuel consumption is similar to the mean loss of the lower heating value. The variability in results is due to different types of engines and operating conditions.

Canakci and Van Gerpen (2001) obtained an increase in BSFC of around 2.5% in their tests with B-20 mixtures and an increase of about 14% with pure biodiesel (B-100). They compared oils and soybean biodiesel fuel in a engine of 57 kW, and showed that the oil origin has no influence.

1.2.3. Thermal Efficiency

The Thermal efficiency is the ratio of power and the energy released by fuel injection, the latter being the product of the fuel mass flow injected and lower heating value of fuel.

According Lapuerta *et al* (2008) this parameter is a more appropriate indicator, than fuel consumption, to compare the performance of different fuels in internal combustion engines. Most authors found similar thermal efficiency when using biodiesel compared to mineral diesel.

1.3. Biodiesel Effects on Engine Emissions

The presence of oxygen chemically bound to the biodiesel molecule has the effect of reducing pollutant concentrations in the exhaust gases due to better fuel combustion in the engine (Lin et al, 2007).

Exhaust emissions from diesel engines operating on pure biodiesel and blends with diesel fuel have been reported in numerous studies, as conducted by the U.S. Environmental Protection Agency (EPA, 2002), where they observed the general trends in emissions and the various components of the gases exhausted from internal combustion engines. As a general trend for emissions of carbon monoxide (CO), an exponential reduction of CO is observed, with increasing percentages of biodiesel.

According Lapuerta *et al* (2008), average CO emissions reduce almost 50% when using biodiesel compared to conventional diesel.

Also according to EPA (2002), emissions of unburned hydrocarbons (THC) and particulate matter (PM), an exponential reduction in emissions of both pollutants is observed as a general trend. The nitrogen from the air, under conditions of high temperature in the combustion chambers, can react with oxygen to form compounds known as NOx (nitrogen oxides), notably NO and NO_2.

Most of the studies showed a slight increase in NOx emissions when using biodiesel, although other researchers pointed out minor variations and a decrease in NOx with increasing biodiesel content in the mixture. The emission rate of NOx is dependent on operating conditions, biodiesel quality and engine type.

1.4. Alternatives for Reduction of NOx Engine Emissions With Biodiesel

The increased use of alternative fuels creates the opportunity of ternary mixtures of diesel, biodiesel and oxygenated compounds such as, for example, ethanol (E-diesel) or dimethyl ether (DME).

According to Ribeiro *et al* (2007), oxygenated additives have been used to reduce the ignition temperature. However, the reduction of particulate emissions through the introduction of oxygenates depends on the molecular structure and oxygen content in the fuel. To reduce particulate emissions, the oxygenates can be added to diesel fuel to produce a compound containing 10 to 25% by volume of oxygen, which, however, will directly affect properties such as density, viscosity, volatility behavior at low temperatures, and the cetane number.

Increasing the concentration of additives (ethanol and ethyl ether) provides a reduction in the cetane number, and an increase in unburned hydrocarbons, but leads to a decrease in CO by 20% compared to pure mineral diesel fuel. The cetane number of ternary mixtures of fuel decreases with increasing ethanol content, due to the low cetane number of alcohol. (De Menezes et al., 2006).

The use of additives such as ethanol leads to a lower combustion temperature in low and medium loads, thereby reducing NOx emissions.

Guariero et al (2009) tested the emissions of 18 ternary mixtures involving diesel, biodiesel from waste cooking oil, anhydrous alcohol and vegetable oil in a bi-cylindrical 27 kW engine with direct mechanical injection naturally aspirated. In this work, they observed other characteristics such as miscibility and stability of mixtures. The stability analysis showed that the mixture of diesel with anhydrous alcohol co-solvents such as biodiesel is stable up to a percentage of 10% anhydrous alcohol for a period exceeding 90 days. Above this percentage (10%) phase separation was found. The effect of oxygenated fuel blends on NOx emissions is complex and not conclusive. The cetane number, fuel density, aromatics and fuel composition can affect the NOx emissions. In their investigations, there was a slight decrease in NOx emissions, between 1800 and 2000 RPM.

1.5. Energy and Exergy Analysis in Engines

Applying the First Law of Thermodynamics in internal combustion engines in a steady state, as shown in Eq. (1).

$$\dot{Q}_{VC} = \dot{n}_c.(\overline{h_p} - \overline{h_R}) + \dot{W}_{VC} \tag{1}$$

Where:

$\dot{Q}_{VC}$ is the heat flux crossing the engine control surface in kW;

$\dot{n}_c$ is the fuel molar flow in kmol/s;

$\overline{h_p}$ is the molar combustion enthalpy in combustion gases in kJ/kmol;

$\overline{h_R}$ is the reactants combustion enthalpy in kJ / kmol;

$\dot{W}_{VC}$ is the power in kW.

The exhaust gas heat can be determined by Eq. (2) below:

$$\dot{Q}_{ex} = \dot{n}_c.(\overline{PCI}) - \dot{W}_{VC} - \dot{Q}_{VC} \tag{2}$$

Where:

$\dot{Q}_{ex}$ is the energy lost by the exhaust gas from the engine in kW;

$\overline{PCI}$ is the molar fuel lower heating value in kJ/kmol.

The engine energy efficiency can be obtained by Eq. (3).

$$\eta = \frac{W_{VC}(kW)}{\dot{n}_c.(\overline{PCI})} \tag{3}$$

The exergy analysis is a powerful tool for assessing the performance of thermal engines as well as taking into account the mass balance, the First Law of Thermodynamics, and also considers the Second Law of Thermodynamics statements. According to this law, it is impossible that there is a thermal engine operating between two reservoirs without a heat rejection for the low-temperature thermal reservoir (to see Figure 1).

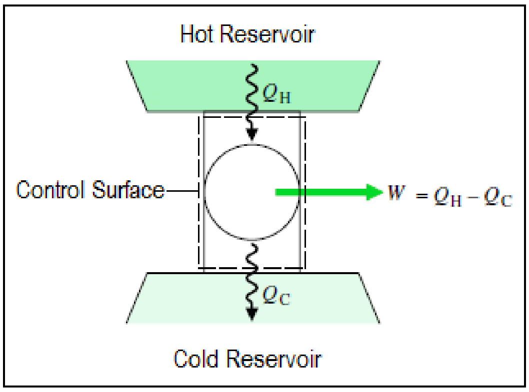

Figure 1. Energy flow in a thermal engine
Moran and Shapiro (2009)

As shown in Figure 1, the maximum work possible for any engine is so limited by Carnot efficiency (Wylen et al., 1995), as shown in Eq. (4).

$$W = (1 - \frac{T_L}{T_H}).Q_H \tag{4}$$

The main features of the exergy analysis are:

- The use of mass conservation, the First Law of Thermodynamics and the application of the Second Law of Thermodynamics;
- The analysis aims to maximize the efficient use of energy resources and environmental issues;
- Identify sites of irreversibility and list the losses in order of importance;
- It is an attribute set of the system and the ambient used as a reference.

In this context, the concept of exergy is the potential performance of work (work theoretical maximum) of an energy source as it comes into equilibrium with the environment in a reversible way (Moran, Shapiro, 2009). The main differences between energy and exergy can be listed as:

- The energy is included in the First Law of Thermodynamics and is conservative;
- The exergy does not obey a conservation law, part of it being destroyed in real processes;
- The exergy analysis takes into account the quality of energy, since not all energy can be converted;

The exergy can be divided into two parts: the thermo-mechanical exergy and chemical exergy. According to (Moran and Shapiro, 2009), by disregarding the kinetic and potential effects, the specific thermo-mechanical exergy can be calculated according to Eq. (5).

$$Ex_{therm} = (h - h_o) - T_o.(s - s_o) \tag{5}$$

Where:

h is specific fluid enthalpy at a condition in kJ/kg;
h_o is the fluid specific enthalpy at the reference ambient in kJ/kg;
T_o is the reference temperature in K;
s is the fluid specific entropy at a condition in kJ/(kg.K);
s_o is the fluid specific entropy in the reference ambient in kJ/(kg.K);

The chemical exergy is the maximum work obtained when the substance under consideration is brought from the environmental state to the dead state by processes involving heat transfer and exchange of substances with the environment (Kotas, 1985). For a liquid fuel, the chemical exergy can be calculated according to equation Eq. (6).

$$\overline{Ex}_{chem} = [1{,}0401 + 0{,}1728\frac{h}{c} + 0{,}0432\frac{o}{c} + 0{,}2169\frac{s}{c}(1 - 2{,}0628\frac{h}{c})].\overline{PCI} \tag{6}$$

Where:
h, c, o and s are the mass fractions of the elements hydrogen, carbon, oxygen and sulfur in fuel composition, respectively. For a mixture of ideal gases the chemical exergy can be calculated as per Eq. (7) (Kotas, 1985):

$$\overline{Ex}_{quim} = \sum x_i.\overline{\varepsilon_0} + \overline{R}T_o.\sum x_i.\ln x_i \tag{7}$$

Where:

xi is the molar fraction of each compound in the mixture;
$\overline{\varepsilon_0}$ is the molar standard chemical exergy of the compound in kJ/kmol;
$\overline{R}$ is the universal gas constant in kJ/(kmol.K).

Finally, the exergy efficiency is the ratio between the exergy output (mechanical work) to the total fuel inlet exergy, as described in Eq. (8):

$$\varepsilon = \frac{\dot{W}_{VC}}{\dot{n}_c.\overline{Ex}_{comb}} \tag{8}$$

Where:

$\overline{Ex}_{comb}$ is the total fuel molar exergy in kJ/kmol.

2. DEVELOPMENT

2.1. Materials and Methods

The tests were performed on a pump driven by a Diesel engine that transports water between two reservoirs, as described in Figure 2.

An internal combustion engine with horizontal single cylinder, 4-stroke and ignition by compression (see table 1) drives a multistage centrifugal type pump (see table 2). For each test cycle, temperatures, pressures, speeds, air emissions and fuel consumption were evaluated with valve V-2 kept open and valve V-1 regulated so as to impose a condition on the pump operation, thereby maintaining constant engine speed. Tests were conducted with equal rotation of the pump with two different fuels. In both cases the engine operated at 1950 RPM. This value was obtained by adjusting the valve V-2 at the pump discharge pipe.

To measure the pump flow, the valve V-2 was closed and then the water accumulated in the upper reservoir. With a level meter in the upper tank with a known volume of 500 L, it was possible to obtain the volumetric flow rate of the pump at each moment. The hydraulic power supplied to the water was calculated with data from the suction and discharge pressures and pump flow rate. The pump efficiency for each flow value was used to determine the engine power.

Initially the tests were conducted with a steady load of 40% for fossil diesel, and then for the ternary mixture of diesel, biodiesel and anhydrous alcohol in the following volumetric proportions: 85% diesel, 10% biodiesel and 5% anhydrous alcohol.

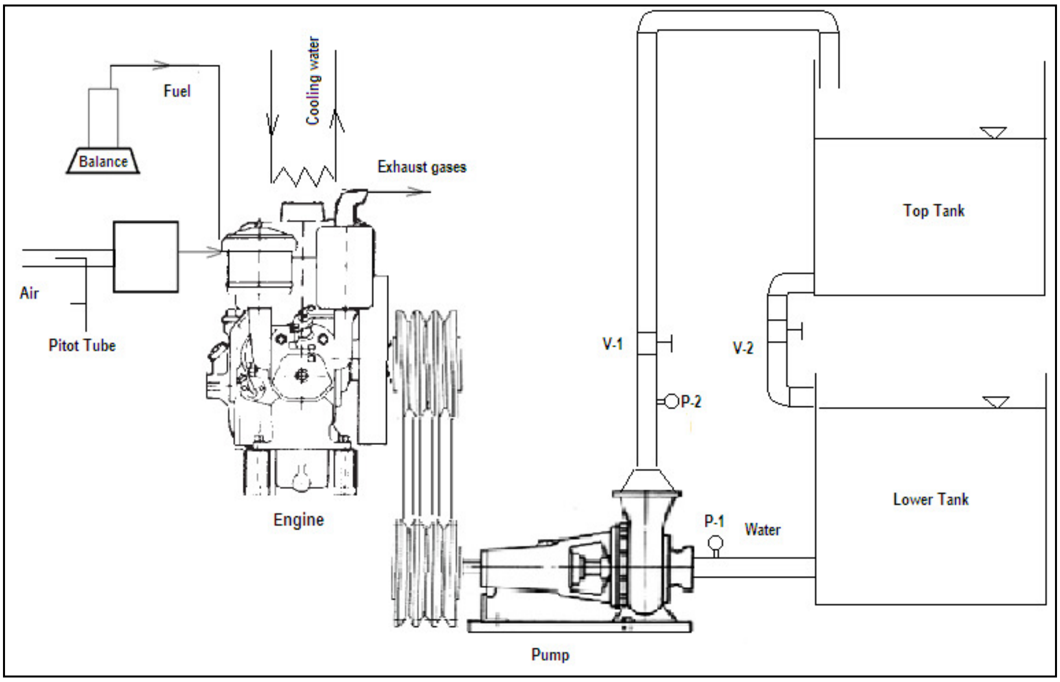

Figure 2. Mounting Hydraulic Flowchart.

Table 1. Main characteristics of the diesel engine.

Characteristics	Information
Model	NSB – 8.18
Maximum Power NBR-6396 (kW)	11.0
Piston Stroke (mm)	106
Piston diameter (mm)	102
Cylind. (cm^3)	866
Lower speed (RPM)	1800
Higher speed (RPM)	2200
Injection	Indirect
Refrigeration	Water
Manufacturer	Yanmar

Table 2 – Main characteristics of the pump.

Characteristics	Information
Model	NE-2
Type	Centrifugal
Stages	4
Impeler diameter (mm)	144
Higher speed (RPM)	3600
Maximum Head (m)	140
Manufacturer	Schneider

For the energy and exergy analysis, the temperature measurements were made with type K thermocouples to assess the engine housing temperatures, inlet and outlet cooling water temperatures, and engine discharge temperature. The relative humidity was measured using a digital hygrometer, while the engine air flow was measured using the Pitot Tube anemometer, and used a buffer to reduce the engine pulsations effects during data acquisition. The Pitot Tube was inserted into admission pipe in 6 points to obtain the air flow. The cooling water flow was measured and kept constant at a value of 0.99 m^3/h for all tests with the two fuels. The engine discharge pressure was evaluated with a Bourdon pressure gauge with glycerin, while the engine body temperature was measured by a digital pyrometer at the same twenty points during the tests with the two fuels. The rotations of the pump and engine were measured by a handheld digital tachometer to evaluate losses due to the pulley-belt coupling.

The fuel rate was obtained by the gravimetric method, by using a balance with a duration of 15 minutes. The emissions were obtained by a gas analyzer capable of assessing the concentration of CO, CO_2, NO, NO_2, O_2. The unburned hydrocarbons concentrations, as well as SO_2, were not evaluated. The main features of the instruments are shown in Tab. 3.

Table 3 – Main characteristics of instruments.

Measuring quantity	Instrument	Manufacturer	Model	Range	Measurement Uncertainty
Inlet temperature	Digital Termometer	ICEL	AN-3070	0 to 50 ºC	± (3%+0,2) ºC
Outlet temperature	DigitalTermômeter/type K termocouple	MINIPA	MT-525/MK T-14	0 to 700 ºC	± 5ºC
Cooling water Inlet and outlet temperatures	DigitalTermômeter/type K termocouple	MINIPA	MT-525	-5 to 120 ºC	± 0,3ºC
Engine body temperature	Digital Pyrometer	RAYTEK	Raynger ST-60	-32 to 600 ºC	± 1%
Engine discharge pressure	Bourdon Gauger with glycerin	BAGAREL	-	0 to 6 bar	± 0,1 bar
Ambient Humidity	Termohigrômetro digital	ICEL	HT-208	0 to 100 %	± 3%
Air flow	Pitot Tube anemometer	TESTO	Testo – 512	0 to 17 m/s	± 0,1 m/s
Engine and pump rotations	Digital Tacometer	MINIPA	MDT-2238A	99999	± 5 RPM
Fuel Consumption	Digital Balance	TOLEDO	9094	0 to 15 kg	5 g
Emissions	Gas Analyzer	TELEGAN	Tempest 50	---	± 2%
Pump discharge pressure	Bourdon Gauger with glycerin	BAGAREL	-	0 to 14 kgf/cm^2	± 0,05 bar
Pump suction pressure	Bourdon Gauger with glycerin	BAGAREL	-	-1 to 2 kgf/cm^2	± 0,05 bar

2.2. Fuels

The mineral diesel and anhydrous alcohol (99.5%) were kindly donated by PetroBahia (Petroleum Distributor of Bahia). The wasted cooking oil (WCO) biodiesel was locally produced in the pilot plant located at Federal University of Bahia (UFBA). The specifications for the biodiesel were determined according to standard EN-14105 (to see table 4).

Table 4 – Main characteristics of biodiesel.

Property	Biodiesel OGR
Monodiacylglycerol (%, w)	0.0489
Diacylglycerol (%, w)	0.1015
Triacylglycerol (%, w)	0.1486
Free glycerol (%, w)	0.1231
Total glycerol (%, w)	0.2988
Viscosity (cSt, 40 ºC)	4.53
Density (20 ºC)	0.888
Ester yield (%)	98

Initially, the equivalent fuel to mineral diesel was determined by combustion products analysis using Eq. (9).

$$C_nH_m + a.(O_2 + 3{,}76.N_2) \rightarrow x.CO_2 + y.CO + z.O_2 + d.H_2O + e.N_2 + t.NO + w.NO_2 \tag{9}$$

The x, y, z, t and w coefficients were obtained using the volume fraction from the gas analyzer, while the d, e, n, m coefficients were obtained by mass conservation of the species in the reaction.

The biodiesel composition was analyzed at the Institute of Chemistry (IQ) at UFBA to obtain the carbon, hydrogen and oxygen percentages (to see table 5).

Table 5 – Biodiesel composition.

Weight (%)	Biodiesel OGR
Carbon	68.76
Hydrogen	10.20
Oxygên	20.75
Nitrogen	0.29

The nitrogen and sulfur contents in biodiesel composition were neglected. The residual water in the anhydrous alcohol composition was also neglected. Thus the composition for each fuel was obtained. The table 6 shows this composition, as well as other characteristics such as molecular weight and lower heating value.

Table 6 – Mineral diesel, biodiesel, and anhydrous alcohol properties.

Property	Mineral Diesel	Biodiesel	Anhydrous alcohol
Tipical composition	$C_{9,84}H_{17,95}$	$C_{18,00}H_{31,80}O_{4,08}$	C_2H_6O
Weight molecular (kg.kmol^{-1})	136.3	313.5	30.07
Lower heating value (kJ.kg^{-1})	42300	38653	28300

2.3. Combustion Reaction for the Ternary Blend

The combustion reaction is described in Eq. (10).

$$x.C_{9,84}H_{17,95} + y.C_{18,00}H_{31,80}O_{4,08} + z.C_2H_6O \ + a.(O_2 + 3{,}76.N_2) \rightarrow$$

$$b.CO_2 + c.CO + g.H_2O + hO_2 + w.NO_2 + j.Ni + i.N_2 \quad (10)$$

The x, y and z coefficients are the fractions used in each fuel ternary mixture, while the other coefficients were obtained using the data reported by the analyzer, and the mass balance of each element.

2.4. Energy Analysis

For the energy analysis, these conditions were adopted:

- The engine operates in steady state;
- The control volume consists only of the internal combustion engine;
- The combustion air and exhaust gases perform a perfect gas mixture;
- The ternary blend is an ideal solution;
- The kinetic and potential energy effects were neglected;
- The atmospheric air composition was assumed as 21% oxygen and 79% nitrogen on a molar basis;
- The energy losses by pulley-belt coupling have been neglected, due to the small difference found in the pump speed and that theoretical speed that would be found by the diameters of engine and pump pulleys.

Equation 1 was used to determine the heat that crosses the control surface. The enthalpy of formation for each fuel was obtained using the lower heating value and the assumption of complete combustion. The exhaust gas heat was determined by the energy balance assuming the entry in the control volume given by the lower heating value of fuel, as described in equation 2. The energy efficiency of the engine was calculated using Equation 3 described above.

2.5. Exergy Analysis

The reference environment for the thermo-mechanical exergy calculation has a temperature (T_o) equal to 25 ° C and pressure (P_o) equal to 1 atm. Moreover, it is admitted that this reference environment is a perfect gas mixture with the following molar composition: 75.67% N_2, 20.35% O_2, 0.03 for CO_2, 3.12% H_2O and 0.83% of other components.

For the evaluation of exergy flows following the heat fluxes, the assumed temperature of the heat source was considered as the one present at the control volume border, where the energy flow crosses it. For example, in the case of cooling water heat flow, the temperature used was the average of inlet and outlet temperatures of cooling water as the engine body heat exchanged, the temperature used was the average of temperatures measured by a pyrometer. The results for fuel consumption, energy balances and summary of exergy flows, in addition to energy and exergy efficiencies are shown in the following item. The relative humidity in the tests was 66%.

3. RESULTS

3.1. Energy Analysis

The fuel $C_{9,84}H_{17,95}$ could be identified as the equivalent mineral diesel fuel by analyzing the combustion products. Table 7 shows the results for specific fuel consumption, energy efficiency and energy flows entering and leaving the engine for the mineral diesel and the ternary mixture.

Table 7 – Energy analysis results.

Property	Mineral diesel	Ternary blend
Specific fuel consumption (g/kW.h)	391.9	408.80
Hydraulic power (kW)	2.88	2.85
Engine power (kW)	5.51	5.41
Inlet energy (kW)	25.58	25.81
Cooling water energy (kW)	5.83	5.55
Engine body energy (kW)	8.51	9.11
Exhaust gases energy (kW)	5.74	5.96
Energy efficient (%)	21.54	21.10

3.2. Exergy Analysis

The table 8 shows the summaries of exergy streams entering and leaving the engine, and the exergy destroyed rate inside the control volume for mineral diesel and ternary mixture fuels.

Table 8 – Exergy analysis results

Property	Mineral diesel	Ternary blend
Inlet exergy (kW)	27.29	27.58
Power (kW)	5.51	5.44
Cooling water exergy (kW)	0.52	0.45
Engine body exergy (kW)	0.82	1.03
Exhaust gases exergy (kW)	3.08	3.02
Destroyed exergy (kW)	17.37	17.64
Exergy eficcient (%)	20.20	19.74

4. CONCLUSIONS

The biodiesel has been shown to be a promising substitute of mineral diesel. Characteristics of biodegradability, low toxicity and renewability make it an important source not only for the Brazilian energy matrix (characterized by heavy use of road transport), but also for the global energy matrix. Its emissions are characterized by having lower CO, PM, THC and SOx emissions rates, however, the NOx emissions tend to grow dependent on the operating conditions, type and engine characteristics, the biodiesel concentration in the blend.

The exergy analysis is a powerful tool that quantifies the potential use of energy resources, being able to locate waste and losses in thermal systems, directing efforts to reduce sources of inefficiency in the processes.

In this study, the energy efficiency obtained for both fuels (mineral diesel and ternary blend) were quite similar. This can be explained by the fact that although the power of the engine is lower and the specific fuel consumption is higher when using the ternary mixture, the heating value of the mixture is lower than that of mineral diesel, resulting in similar efficiencies. The exergy analysis shows the same trend. However, as the amount of exergy that enters each fuel is greater than the amount of energy, the exergy efficiency is slightly lower than energy efficiency.

The exergy analysis shows that although there are generous energy flows accompanying the dissipated heat in the cooling water and the engine housing, the exergy accompanying these heat fluxes is negligible. Much of the exergy is destroyed within the engine due to the activation energy required for the sustainable combustion reaction. A further study on the combustion could reduce that percentage. Further studies on the use of wasted exergy by the exhausted gases are justifiable because of the high percentage of exergy accompanying these gases.

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