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# Crambe oil (Crambe abyssinica) preheated in diesel engine

## *Óleo de Crambe (Crambe abyssinica) pré-aquecido em motor ciclo Diesel*

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**Abstract**: Studies indicate derivatives of vegetable and animal oils as substitutes for petrodiesel. However, their use as fuel requires changes or strategies to reduce their viscosity. Therefore, an experiment was carried out using crambe oil (CR) preheated up to 100 °C in a diesel engine (PD). CR and DE were evaluated at every 15 hours of operation, in four regimes, up to 100 hours of work. The regimes were, 1100 rpm without load, 1800 rpm without load, 1800 rpm with 51% and 66% of nominal power. We observed that the consumption of CR was higher than that of PD, with a more pronounced difference in regimes under load, with a greater loss of relative power being observed in the use of CR when changing the load. There was no difference between the two fuels regarding thermal efficiency. When the cooling fluid and lubricant were analyzed, higher temperatures were observed for the CR, but the temperatures of the exhaust gases and the lubricant pressure were higher for the PD. At the end of the test, CR presented increased pressure and injector opening pressure, and the injector elements showed carbonization, which were difficult to remove, wear and signs of overheating. There was no evidence of oil degradation.
Keywords: biofuel, vegetable oil, fuel consumption, bioenergy, sustainable development

***Resumo***: *Estudos apontam derivados de óleos vegetais e animais como substitutos ao petrodiesel. Porém, o uso destes como combustível requerem transformações ou estratégias para reduzir sua viscosidade. Sendo assim realizou-se experimento utilizando óleo de crambe (CR) pré-aquecido a 100 °C em motor ciclo Diesel. Avaliou-se CR e PD, a cada 15h de funcionamento, em quatro regimes, até 100 h de trabalho. Os regimes foram, 1100 rpm sem carga, 1800 rpm sem carga, 1800 rpm com 51% e com 66% de potência nominal. Observou-se que o consumo de CR foi superior ao de PD, com diferença mais pronunciada nos regimes sob carga, observou-se perda de potência relativa maior no uso de CR quando da mudança de carga. Não houve diferença entre os dois combustíveis para a eficiência térmica. Para o fluído de arrefecimento e lubrificante, foram observadas temperaturas maiores para o CR, porém a temperatura dos gases de exaustão e a pressão do lubrificante foram maiores para o PD. Ao fim do ensaio, para CR, houve aumento das pressões de compressão e de abertura do injetor, e os elementos injetores apresentaram carbonização, de difícil remoção, desgaste e sinais de superaquecimento. Não houveram evidências de degradação do lubrificante.*
*Palavras-chave: biocombustível, óleo vegetal, consumo de combustível, bioenergia, desenvolvimento sustentável*

## 1 Introduction

The release of greenhouse effect gases by the use of fossil fuels is a concern in the global scientific discussion. In such scenery, one alternative is the substitution of petrodiesel by vegetable oil derivatives (VO), since when they are transformed, and/or used in *blends*, these oils present interesting characteristics to be used as fuel (MAT et al., 2018; RAMAKRISHNAN et al., 2018; PRABU et al., 2018, VARUVEL et al., 2018; KOTHANDAN & MASIMALAI, 2018; CHIDAMBARANATHAN et al., 2020, and CHIDAMBARANATHAN et al., 2022).

Transformation processes imply increased costs, energy consumption, and contaminations. Thus, one alternative would be to use VO without transformations. However, due to their high viscosity, these oils might cause problems related to atomization, pumping, irregular combustion, formation of deposits, lubricant contamination, excess gas emission, and decreased durability (AGRAW et al., 2019, BAKTHAVATHSALAM et al., 2019).

Heating VO, either pure or in blends with PD reduces viscosity, improves the injection and ignition delay features (increased cetane number), and favor combustion (PRADHAN et al., 2014; BAKTHAVATHSALAM et al., 2019). The literature presents reports of consumption reduction, formation of deposits, lubricant contamination, and increased thermal efficiency when compared to the unheated oil (ALMEIDA et al., 2002; JAIN et al., 2017).

Another factor to be considered is the importance of the physicochemical characteristics of VO (HELLIER et al., 2015; RAMAKRISHNAN et al., 2018). When investigating linseed, crambe, jatropha curcas, and canola oils used as fuel in diesel engines, crambe presented consumption, power, and particulate emission similar to that of PD (DELALIBERA et al., 2017).

In this study, preheated crambe oil was used and the factors evaluated were fuel consumption, power loss, thermal efficiency, and engine and lubricant temperatures in comparison to DE.

## 2 Material and methods

The experiment was developed at the Institute for the Rural Development of Paraná (IDR-Desenvolvimento Rural do Paraná), Londrina center – PR. Two types of fuel were used, namely, preheated crambe (*Crambe abyssinica* Hochst) (CR) vegetable oil, at 100 °C, and conventional fuel, diesel B5 and S500 (PD) as witness.

The CR VO was obtained using mechanical extraction in an Expeller press followed by filtering (0.5 μm). The fuels were characterized regarding gross calorific value (GCV) (ASTM D240-17). The CR kinematic viscosity was estimated at 40°C and 100 °C, using a Cannon-Fenske capillary viscosimeter (ASTM D445-06).

The test bench contained a stationary diesel engine, YANMAR® (B9C), mono-cylinder, four stroke, mechanical and indirect injection, and maximum power of 5.88 kW@1.800 rpm, and an electrical generator with 4 kW nominal capacity (DELALIBERA et al., 2017).

The procedures followed prior to the test included lubricant, pump element, and fuel nozzle substitution, as well as the injector opening pressure, compression pressure verification, and valve adjustment.

The alternation of fuels was carried out using a three-way two-position manual valve, positioned at the entrance of the injection pump. CR was preheated via electrical resistance, 450 W, in a 140 mm aluminum tube, inside which the VO circulated. To control the temperature, a digital thermostat (N321®, NOVUS) was used along with a K-type thermocouple sensor, inserted in the heater. The system was regulated so that the VO entered the system at 100 °C.

To simulate loads, the generator was coupled to the lamp resistive bank, which allowed the application of two power absorption regimes, that is, 3.0 and 3.9 kW, respectively, at 51% and 66% of the engine nominal power, and 1,800 rpm. To measure the engine speed, an incremental encoder (1,024 pulses per revolution) with 33.33 Hz acquisition was coupled to the crankshaft.

The room temperature at the time of the test was controlled with a thermostat (N321®) coupled to a PT100 sensor, which would be activated at temperatures over 25 °C.

The engine was started with PD and after heating and the cooling system temperature stabilization, it was changed to CR. Before stopping the engine, it was returned to PD for 15 minutes. The engine worked uninterruptedly for 8 hours a day up to 100 h of test.

At time zero and at each 15h after the engine had been started, evaluations of consumption and power loss in both treatments were carried out. This means that there were seven evaluation times: 0, 15, 30, 45, 65, 80, and 95 hours. Between the evaluations, the engine operated with CR in the regime of 51% power absorption and 1.800 rpm.

After the engine had been working for 50 h, the test was interrupted for analyses, in which we verified the wear of the injection nozzle elements and the injection pump, the injector opening pressure, the compression pressure, and the lubricant oil substitution was carried out.

Fuel mass evaluations were carried out using a system of automated reading and recording, which determined the CR and PD masses and fuel return, according to the reservoirs. Only the injector nozzle return was evaluated since the injector pump return goes back to its own input. The reading frequency was 0.5 Hz.

The assessments were carried out in four engine operation regimes, namely, 1,100rpm speed (low gear), 1,800rpm speed without load (free acceleration), 1,800rpm with 51% of the engine power, and 1,800rpm with 66% of the engine power. For the evaluations, each regime and fuel were in operation for 15min, with consumed fuel mass reading at each 150 s (six repetitions).

To analyze the consumed fuel mass, normality and homoscedasticity were tested. After that, the variance analysis was carried out, with block design and split-plot design (2x4x7; fuels, regimes, and time of use), with the insertion of non-randomization errors for all factors. To compare the means, the Tukey test was employed at a 5% probability level. Specific consumption was calculated for the regimes under load (PRADHAN et al., 2014).

To evaluate power loss, we used the variation in revolutions provoked by the load alternance (DELALIBERA et al., 2017). This variable was calculated by considering the difference between area under the rotation curve in time with the initial power demand and curve with the new submitted demand. The relative power loss evaluations were carried out in three conditions of power demand at 1,800 rpm speed. The loads employed were 51% nominal power (3.0 kW), 66% (3.9 kW) and the application of 0.9 kW over the 3.0 kW load regime, that is, by adding 15% of the total power.

Ten repetitions were performed for this variable at each 10s, between each submission condition and load removal. To calculate PPR, we used the interval of 5s after load application, since this was the maximum time needed between the speed decrease peak, resumption, and start of the rotation stabilization. Subtracting the area under the speed curve in the initial power, within 5s before the load input, and the area below the acceleration resumption curve, results in a third area. The higher this value is, the greater the relative power loss is.

Thermal efficiency was determined as the ratio between the engine output power and the theoretical power supplied by the fuel (WANDER et al., 2011; PRADHAN; RAHEMAN; PADHEE, 2014). The theoretical power was calculated considering the consumption (treatments with work under load) and the calorific value obtained experimentally. Test t was employed to compare the theoretical power means.

To determine the temperatures, K-type thermocouple sensors were employed. For the cooling fluid, the sensor was placed in the engine block, immersed in the cooling fluid, the lubricant sensor was immersed in the center of the crankcase, while the exhaustion gas sensor was placed in the center of the exhaust port. The readings were carried out at each 15 hours of engine work, always comparing CR and PD. All temperatures were monitored with 0.05 Hz acquisition.

After obtaining the results, normality and homoscedasticity were tested. For parametric variables, variance analysis with a block design and split-plot scheme in the 2x4x7 time was performed, estimating the errors of non-randomization of all factors, followed by the Tukey test ($p<0.05$) for mean comparison ($p<0.05$). Regarding non-parametric variables, the Friedman analysis ($p<0.05$) was used.

In the lubricant analysis, the lubricant system work pressure was monitored, with a 0.5 Hz acquisition frequency. At each 15 hours of engine operation, a lubricant sample was collected for laboratory analysis. The new lubricant was also analyzed (zero time), totaling seven samples. Whenever necessary, the lubricant was replenished. The multigrade mineral lubricant SAE 15W40 (Ambra Super Gold) was used. At the end of 50 h, the lubricant was substituted.

The lubricant was analyzed for the following factors: soot content (ASTM D7686), viscosity at 40 °C (ASTM D445), dilution per fuel (ASTM D3524), water content, precipitation index (ASTM D91), total base number (TBN) (ASTM D4739), pentane insolubles (ASTM D4055), dispersion power (ASTM D7899), contamination index (ASTM D7900), weighted loss (ASTM D7901), oxidation, nitration, and sulfonation (ASTM D7889), contaminant elements(ASTM D5185), soot and oxidation products, silicon oxide and ferrous alloys (ASTM 7684), and ferrous particle index (IPF).

The variables were recorded using the datalogger Campbell Scientific (CR 5,000). The software used in the visualization, treatment, and statistical analyses included Catman Easy-AP 3.3.5® (HBM), Microsoft Office Excel, BioEstat 5.0, and SisVar 5.6.

## 3 Results and discussion

The CR kinematic viscosity values were 49.41 and 9.96 mm² $s^{-1}$ at 40°C and 100 °C, respectively, with a 79.84% reduction. Despite the significant decrease, viscosity was still higher than the recommended maximum values according to ANP 50/2013 (BRASIL, 2013) and 45/2014 (BRASIL, 2014), which are 5.0 and 6.0 $mm^2 s^{-1}$ at 40 °C for PD S500 and biodiesel, respectively.

The superior calorific value (OCS) obtained by CR was 41.79 MJ $kg^{-1}$ (± 0.36), 8.62% lower than that obtained by PD, which reached 45.73 MJ $kg^{-1}$ (± 0,72). Due to the oxygen present in their molecules, the calorific value of vegetable oils is lower than that of PD (BALAKRISHNA, 2012).

Despite the significant interaction between time and consumption, we opted for disregarding the time factor, since it did not present any adjustment of significant statistical models that indicated such trend. In all regimes, significant difference was found between consumption for different fuels, in which CR showed higher values, on average, 8.84% higher in the low gear, 3.46% in the load-free 1,800 rpm, 8.20% for 3.0 kW@1.800 rpm (51%), and 9.34% for 3.9 kW@1.800 rpm (66% of the nominal power) (Table 1).

Table 1. Consumption per hour (g $h^{-1}$) of fuels CR 100 °C and PD according to the regime.

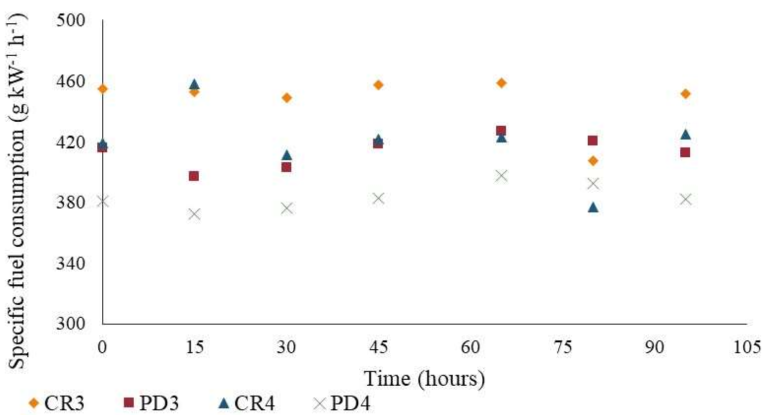
| Regime | Treatment* | Mean (g $h^{-1}$)** |
|---|---|---|
| Low gear | CR 100 °C 1 | 410.16 b |
| | PD1 | 376.85 a |
| 1,800 rpm without load | CR 100 °C 2 | 635.88 b |
| | PD2 | 614.64 a |
| 1,800 rpm with 51% load | CR 100 °C 3 | 1342.10 b |
| | PD3 | 1240.37 a |
| 1,800 rpm with 66% load | CR 100 °C 4 | 1635.34 b |
| | PD4 | 1495.66 a |

*CR1 – crambe oil in the low gear condition; PD1 – Petrodiesel in the low gear condition; CR2 – load-free crambe oil in acceleration at 1,800 rpm; PD2 – Petrodiesel in load-free acceleration at 1,800 rpm; CR3 – crambe oil with a 3.0 kW load @1.800 rpm; PD3 – Petrodiesel with a 3.0 kW load@1.800 rpm; CR4 – crambe oil with a 3.9 kW load @1.800 rpm; PD4 – Petrodiesel with a 3.9 kW load@1.800 rpm

**Means followed by different letters in the same regime differed one from another in the Tukey test ($p>0.05$)

Our results are similar to those already reported, with higher consumption of the preheated CR at 100 °C in relation to PD when load was applied (DELALIBERA et al., 2017). With the castor bean VO use in blends with PD and butanol, higher specific consumption was observed with the decrease in the PD proportion (QI et al., 2021). However, in low load conditions, no difference was found in the consumption of rapeseed VO and PD (NWAFOR, 2003). No statistical analysis was performed for the fuel return, since it was considered irrelevant, that is, < 1 %.

The general means of specific consumption were 447.37 g $kW^{-1} h^{-1}$ with CR and 413.46 g $kW^{-1} h^{-1}$ with PD, in the regime employing 51% load, and 419.32 and 383.50 g $kW^{-1} h^{-1}$ for 66% of the nominal power load (Figure 1).




CR3 – crambe oil with a 3.0 kW load@1.800 rpm; PD3 – petrodiesel with a 3.0 kW load@1,800 rpm; CR4 – crambe oil with a 3.9 kW load@1,800 rpm; PD4 – petrodiesel with a 3.9 kW load@1,800 rpm

Figure 1. Specific consumption (g $kW^{-1} h^{-1}$) of the engine-generator set with CR at 100 °C and PD in the load regimes at each 15 hours of test.

The specific consumption reduction with load increase trend, and the higher specific consumption of VO when compared to PD were already reported (MARTINI et al., 2012; PRADHAN et al., 2014; JAIN et al., 2017). Another finding was the variation of values measured in the time of 80 hours. However, no statistical difference was observed in those values and the absence of significant difference was also observed for the parameters represented according to the time of use of the fuels.

The relative power loss (PPR) significant increase was observed with the increase in the applied load with both fuels and when comparing them (Table 2).

Table 2. Relative power loss (relative loss in the number of revolutions in 5 s after load application).

| Treatment | Load applied | | |
|---|---|---|---|
| | 51% + 15% | 51% | 66% |
| Crambe 100 °C (CR) | 0.66 b | 1.48 b | 1.74 a |
| Petrodiesel (PD) | 0.51 a | 1.43 a | 1.92 b |

Means followed by the same letter in the column did not differ one from another in the Tukey test ($p<0.05$)

The PPR values were higher for CR, except when 66% of the nominal power was applied, when CR showed the best performance. The smallest variations with PD indicate higher stability when the engine is in operation. A study on CR showed that preheating increased PPR (DELALIBERA et al., 2017). However, that was a short-lasting investigation, thus it might not represent accurately the cumulative effect of this fuel use.

When investigating theoretical power, no significant difference was observed between both fuels, with 1.1% mean variation between the powers with a load of 51% of the nominal power and 0.08% with the 66% load (Table 3). Such similarity between the theoretical powers is due to the compensation of the CR lower calorific value through increased consumption, so that the combustion in both cases results theoretically in the same amount of energy.

Table 3. Mean theoretical power supplied and thermal efficiency estimated for the fuels CR at 100 °C and PD to the engine-generator set according to the load regimes.

| Regime | Treatment | Theoretical power (kW) | Significance in the "t" test | Thermal efficiency (%) |
|---|---|---|---|---|
| 3.0 kW@1,800 rpm (51% of the nominal power) | Crambe 100 °C (CR) | 15.580 | p=0.5524 | 19.26 |
| | Petrodiesel (PD) | 15.756 | | 19.04 |
| 3.9 kW@1,800 rpm (66% of the nominal power) | Crambe 100 °C (CR) | 18.983 | p=0.9599 | 20.54 |
| | Petrodiesel (PD) | 18.999 | | 20.53 |

Comparison of means using the "t" test where $p>0.05$ does not depict a significant difference.

The use of VO reduces the effective power of engines (ALTIN et al., 2001). A 4% power reduction was reported for soybean oil at 30 °C and 1.7% for the same vegetable oil at 60 °C (WANDER et al., 2011). Power reduction might be caused by the VO higher viscosity and lower calorific value. (ALTIN et al., 2001). However, in an indirect injection engine, soybean oil heated at 68 °C showed power that was 6.7% higher than that of PD and, in high revolution, the power was 12.7% higher (SCHLOSSER et al., 2007).

Although the PD and CR input energies are similar, there are differences in the engine performance, as observed in the PPR analysis. In addition, different fuels require different conditions for complete combustion due to the fuel viscosity and physicochemical composition, compression ratio, and ideal air-fuel mixture, thus generating distinct performance.

Due to the similar theoretical powers, the thermal efficiencies were also similar. The increased thermal efficiency by the VO use in comparison to PD was also observed for different preheated VO (Nwafor, 2003). On the other hand, some studies reported reduced thermal efficiency such as 28.51% for PD and 27.69% jatropha oil at 100 °C (CHAUHAN et al., 2010). In another study using jatropha (70 °C), a 5.18% reduction in thermal efficiency was observed in the maximum power condition (PRADHAN et al., 2014). When using sapodilla (*Manilkara zapota*) oil, an 88% thermal efficiency was reported in relation to PD (PRABU et al., 2021).

The different results confirm that the VO physicochemical compositions and the type of technology of the engine used influence performance. Regarding the technology, higher thermal efficiency was reported with a blend of 20% VO, when the plunger was coated with ceramic (multi-lanthanum) (BAKTHAVATHSALAM et al., 2019).

No significant trend was observed in the values of the temperatures of the different systems in relation to the time the engine worked. Therefore, we did not calculate factors within time only comparing the means obtained in the test total time (Table 4).

The cooling system temperature when CR was used was higher than that of PD in all regimes. However, little difference was observed between both fuels.

Table 4. Temperature of exhaustion gases, cooling fluid, lubricant, and lubricant pressure in the engine according to the fuel and work regime.

| Engine system | Treatment | Low gear | Load-free 1,800 rpm | 51%@1,800 rpm | 66%@1,800 rpm |
|---|---|---|---|---|---|
| *Exhaustion gases (°C) [1] | Crambe | 138.10 a A | 166.30 a B | 301.21 a C | 366.25 a D |
| | Petrodiesel | 144.68 b A | 179.12 b B | 320.31 b C | 389.22 b D |
| *Cooling (°C) [1] | Crambe | 96.59 b A | 97.07 b B | 97.37 b C | 97.75 b D |
| | Petrodiesel | 95.70 a A | 96.17 a B | 96.59 a C | 96.62 a C |
| **Lubricant (°C) [2] | Crambe | 59.05 b A | 62.13 a AB | 62.12 a BC | 63.89 b C |
| | Petrodiesel | 58.78 a A | 59.61 a AB | 60.35 a BC | 62.81 a C |
| *Lubricant pressure (MN $m^{-2}$) [1] | Crambe | 1.01 a A | 1.86 a C | 1.79 a BC | 1.69 a B |
| | Petrodiesel | 1.23 b A | 2.03 b C | 1.86 a B | 1.78 b B |

Means followed by the same small letter in the column and capital letter on the line did not differ from one another, where [1] – differences given by the Tukey test ($p<0.05$) and [2] – by the Friedman test ($p<0.05$); * mean; ** median

The lubricant temperature was higher with CR in the low gear and with 66% load regimes. The temperature of exhaustion gases increased when the speed and load increased with both fuels, which was expected, however, CR resulted in lower temperature.

The VO use tends to increase the temperature of the engine exhaustion gases when compared to PD (PRADHAN et al., 2014; DELALIBERA et al., 2017; JAIN et al., 2017, CHIDAMBARANATHAN et al., 2020). In an engine with palm oil, no alteration was observed in the temperature of exhaustion gases (ALMEIDA et al., 2002). Lower temperatures of exhaustion gases indicate higher thermal efficiency (CHAUHAN et al., 2010; PRADHAN et al., 2014).

Another study evaluated the addition of 5% coconut oil and 5% palm oil to PD and reported, respectively a 1.58% reduction and a 1.42% increase in the temperature of exhaustion gases when compared to PD. Such effect was ascribed to the higher amount of saturated fat acids in the coconut oil, which favors combustion when compared to the palm oil (KALAM et al., 2011). When comparing punnai (*Calophyllum inophyllum*) oil and petrodiesel in maximum load, temperatures that were 20.8% higher were observed with the vegetable oil use (CHIDAMBARANATHAN et al., 2020). Different viscosities lead to different combustion speeds (VENKATESAN et al., 2019).

As regards the lubrication system, lower pressure was observed with CR between the fuels in regimes 1, 2, and 4. CR showed a higher temperature trend that that of PD, which resulted in lower lubrication pressure, probably due to viscosity reduction.

The analysis showed variation of up to 4% in viscosity when compared to the new lubricant (Table 5). When sunflower VO was used, without preheating due to incomplete combustion, a sharp increase in the lubricant viscosity was reported (MAZIERO et al., 2007). Lubricant viscosity reduction was also observed (ALMEIDA et al., 2002, DELALIBERA et al., 2009). Lubricant dilution is usually caused by combustion problems due to faulty atomization and low volatility of vegetable oils (ALMEIDA et al., 2002). The presence of VO in the lubricant might provoke polymerization with thickening and formation of suspended solids (SIDIBÉ et al., 2010).

Another relevant factor observed was the absence of soot (combustion product) contamination, which indicated satisfactory combustion (Table 5). Soot in the lubricant might cause increased viscosity (HASANNUDIN et al., 2016). The results obtained showed that the CR combustion tended to be complete. Indirect combustion engines use a higher compression rate and therefore might show lower injector carbonization and lubricant contamination.

The total base number (TBN) indicates the lubricant good condition, since its substitution is recommended whenever TNB reaches half of the initial value and, in this case, it showed 8.75% maximum variation in relation to the witness. TBN reduction results in increased oxidation and viscosity (PEREIRA, 2018).

Table 5. Physicochemical analysis of the lubricant during the test with preheated crambe vegetable oil.

| Experimental time | 0 h | 15 h | 30 h | 45 h | 65 h | 80 h | 95 h |
|---|---|---|---|---|---|---|---|
| Lubricant replenishment reference | New | 15 h | 30 h | 45 h | 15 h | 30 h | 45 h |
| Soot (%) | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Viscosity at 40 °C (cSt) | 102.0 | 105.4 | 103.1 | 103.7 | 106.2 | 104.4 | 101.7 |
| Dilution (%) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Water (%) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Precipitation Index (%) | 0.05 | 0.10 | 0.10 | 0.15 | 0.05 | 0.10 | 0.10 |
| T B N (mg KOH $g^{-1}$) | 8.23 | 8.27 | 8.50 | 8.95 | 8.63 | 8.60 | 8.03 |
| Pentane insolubles | 0.04 | 0.01 | 0.02 | 0.03 | 0.00 | 0.03 | 0.02 |
| Dispersing power | 100 | 77 | 75 | 83 | 76 | 75 | 74 |
| Contamination index | 0.1 | 0.1 | 0.3 | 0.2 | 0.1 | 0.2 | 0.3 |
| Weighted loss | 0 | 2 | 8 | 3 | 2 | 5 | 8 |
| Aluminum (ppm) | 0.10 | 3.80 | 7.62 | 12.13 | 4.96 | 7.67 | 11.99 |
| Copper (ppm) | 0.10 | 3.50 | 6.24 | 8.71 | 3.40 | 6.21 | 8.86 |
| Chrome (ppm) | 0.10 | 2.50 | 4.32 | 6.56 | 1.92 | 3.47 | 5.97 |
| Iron (ppm) | 0.73 | 150.0 | 202.9 | 256.4 | 105.2 | 145.6 | 182.8 |
| Silicon (ppm) | 7.47 | 8.43 | 10.04 | 12.60 | 8.88 | 9.88 | 12.38 |
| Lead (ppm) | 0.10 | 14.28 | 19.92 | 22.79 | 10.80 | 14.62 | 16.68 |
| Zinc (ppm) | 1385 | 1379 | 1375 | 1376 | 1427 | 1373 | 1396 |
| Tin (ppm) | 0.10 | 0.44 | 1.70 | 3.19 | 0.13 | 1.26 | 2.54 |
| Calcium (ppm) | 1288 | 1300 | 1316 | 1350 | 1356 | 1326 | 1378 |
| Sodium (ppm) | 0.10 | 0.25 | 0.58 | 1.15 | 0.60 | 0.78 | 0.97 |
| Boron (ppm) | 0.51 | 0.69 | 0.75 | 0.84 | 0.62 | 0.63 | 0.71 |
| Magnesium (ppm) | 1067 | 1076 | 1087 | 1106 | 1118 | 1088 | 1118 |
| Manganese (ppm) | 0.10 | 0.10 | 0.37 | 0.87 | 0.10 | 0.08 | 0.50 |
| Phosphorus (ppm) | 1191 | 1180 | 1178 | 1189 | 1224 | 1171 | 1204 |
| Oxidation (Abs) | 5.861 | 7.054 | 8.366 | 9.746 | 7.177 | 8.684 | 10.110 |
| Nitration (Abs) | 5.185 | 5.647 | 6.074 | 6.489 | 5.660 | 6.132 | 6.448 |
| Sulfonation (Abs) | 12.461 | 13.701 | 14.388 | 15.421 | 15.693 | 14.656 | 16.086 |
| Soot/due to oxidation | Normal | Normal | Normal | Normal | Normal | Normal | Normal |
| Silicon oxide | Normal | Trace | Trace | Limit | Normal | Trace | Trace |
| Iron alloys >5<15 µm | Normal | Attention | Attention | Limit | Trace | Attention | Attention |
| Iron alloys >15<70 µm | - | - | Trace | Trace | - | - | - |
| Ferrous particle index (IPF) | 6 | 59 | 103 | 180 | 61 | 95 | 115 |

Most elements showed increased content, which might have resulted from engine wear, admission air, or fuel (Table 5). Aluminum, copper, chrome, iron, lead, and tin are characteristic of engine wear (HASANNUDDIN et al., 2016).

Aluminum, silicon and iron can also have an external origin, because they can be found in particles (characteristic of the region soil) suspended in the atmosphere (HASANNUDDIN et al., 2016). The engine used was originally composed of an air filter of the oil bath type in the admission system, without a lubricant filter.

We also observed high presence of metallic elements. They might catalyze the lubricant oxidation. Therefore, the useful life of the lubricant was reduced with the preheated CR use, even if the causes might not be necessarily linked to the fuel.

Some elements were found in high concentrations in the lubricant as its initial composition such as zinc, calcium, magnesium, and phosphorus (over 1,000 ppm). They are part of the additives that act as protectors of the metallic surfaces (HASANNUDDIN et al., 2016; PINHEIRO et al., 2017).

Also, the elements phosphorus, calcium, magnesium, and sodium, whose concentrations increased, all of them along with potassium might have come from the VO. The lubricant mean temperature was 57.46 °C, while the highest temperature recorded was 78.17 °C, lower than the critical value, that is, 120 °C.

At zero time, the compression pressure was 1.52 MN $m^{-2}$ (15.5 kgf $cm^{-2}$) and after 100 hours, the mean value 1.70 MN $m^{-2}$ (17,38 kgf $cm^{-2}$) was obtained. This variation is within the limits recommended by the manufacturer. Thus, we considered that no damage was provoked to the combustion chamber due to wear and/or carbonization.

Two verifications in addition to that of the zero time were carried out for the injection system. At 50h the opening pressure decreased 0.49 MN $m^{-2}$ (5 kgf $cm^{-2}$), within the limits recommended by the manufacturer. Although the tightness test presented suitable values, the atomization test showed the formation of large drops. In that case, new adjustment of the injector opening pressure was carried out. In the 100 h evaluation, an increase from 14.2 to 15,6 MN $m^{-2}$ was observed in the injector opening pressure.

The tightness test also indicated excess fuel return, probably caused by wear of the element body due to the increased opening pressure or work temperature. The atomization test showed normal results. Since the injector opening pressure excess was verified, it was calibrated again. However, the tightness test did not obtain suitable results, wear and carbonization (difficult to remove) as well as overheating signs were observed (Figure 2).

(a) (b)

Figure 2. a) Injector nozzle carbonization; b) overheating signs

# 4 Conclusions

a) The consumption of preheated cramb oil was higher than that of petrodiesel and the difference between the treatments was more noticeable in tests under load;
b) The preheated crambe oil relative power loss was higher, except for the condition in which heavier load was applied;
c) Both fuels presented the same efficiency;
d) No abnormalities were observed in the temperatures of cooling or lubrication fluids;
e) No evidence was found of lubricant degradation due to contaminants presented by the use of preheated crambe oil;
f) Wear and overheating of the injector element were observed.

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