Use of JP-8 on VBR Pandur II 8x8 – Experimental study on test bench

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ABSTRACT

The main goal of this investigation is to test the engine of the wheeled armored vehicle Pandur II 8x8 fed with the Jet Propellant 8 (JP-8) fuel, and compare the engine performance with the normal diesel fuel thus contributing to the implementation of the Single Fuel Concept (application of one single fuel for ground vehicles and aircrafts on battlefield, by all armed forces of the NATO countries).

On full load tests, treated JP-8 was the one with higher values of power and torque reached by the engine, and a lower value of brake specific fuel consumption (bsfc) and hourly consumption. At variable load tests, normal diesel fuel revealed a residual higher value of bsfc and hourly consumption, compared with the other two tested fuels, at medium to high loads. There's reason to believe the good performance of the JP-8 fuel is due to the high fuel injection pressures exerted by the HPCR system equipping this engine, hence, reducing the effect of the lower cetane number, empowering a better fuel/air mixture effects provided by the lighter fuel (JP-8) inside the cylinder.

A direct replace of the normal diesel fuel by the normal JP-8 fuel would result in a cost reduction of 52.6 %, and this reduction would be of 19.19% if that replacement was done by treated JP-8.

The increasing sulfur content among the engine oil suggests that an engine working with JP-8 fuel may be subjected to an increasing wear, due to the higher sulfur content among this fuel.

Keywords: Fuel, Power, Load, Brake Specific Fuel Consumption, Injection Pressure

INTRODUCTION

An attempt to obtain logistics benefits led NATO to implement one Single Fuel Policy (SFP), which consists on using one single fuel for aircrafts and ground vehicles. This happens because NATO armed forces strongly need their ground vehicles to accomplish their missions on all territories where they are present.

This causes a big dependency on the fuel needed for the propulsion of these vehicles, mainly on the logistics behind them, since the terrestrial forces on the battlefield need strong autonomy because of their big maneuvering capacity and fire power.

Since Portugal is also a NATO member country, the Portuguese Army has a role on the effective implementation of this Single Fuel Policy, contributing for a better performance of NATO and all the armed forces of its' member nations.

The chosen fuel for this Single Fuel Policy was the Jet Propellant 8 (JP-8), F-34 on NATO designation. This fuel is similar to the NATO F-35 (JP-7, commercial Jet-A1), which is improved with viscosity improver and freezing inhibitor.

Studies have been conducted by the NATO member countries, either by institutions directly linked to NATO (like *NATO Fuels & Lubricants Working Group*), either by some more independent universities and academies in partnership with those countries armed forces.

The results and experiences conducted since 1986, the time when the Single Fuel Concept (SFC) was created, have been widely positive. However, further investigation is needed for an effective implementation of the SFP, fulfilling the objectives that led to its' creation. Naming, to grant that the replacement of diesel fuel by JP-8 fuel on diesel engines do not harm the equipment with malfunction of these. Also, to make sure that the exhaust emissions of these internal combustion engines are not impaired because of fuel changing, regarding that climate changing plays an important role on all activities of mankind, leading to the creation of specialized entities which compete the regulation of climate changing gases.

The investigation supporting this article, is part of the contribution of the Portuguese Army for the Single Fuel Concept, supported by many other studies conducted among Portugal and other NATO member countries. Therefore, the purpose of this investigation is to compare and quantify the engine performance variation caused by the diesel fuel replacement by JP-8 in full load and variable load conditions, regarding the torque, power and fuel consumption extracted by the engine. It also aims to assess the consequences of the fuel replacement, considering that the conditions for that study are not the ideal ones, due to the nature of the tests performed.

The present study is part of the Portuguese contribution with NATO, for conducting the necessary investigation for the successful implementation of the SFC, quantifying its benefits and hazards for the existing equipment, and evaluating financial parameters.

EQUIPMENT, FUELS AND EXPERIMENTAL PROCEDURE

The equipment tested consisted of a Cummins ISLe T450 HPCR engine, used in VBR Pandur II 8x8 vehicles, equipping the Portuguese Army.

The test bench used in the measurements is installed in *Unidade de Apoio Geral de Material do Exército* (UAGME) and has, as main characteristics [1], the following ones:

Maximum rotation speed: 7000 rpm +/- 0.5rpm;
Maximum torque: 2400 Nm +/- 0.0005Nm;
Maximum power: 470 kW +/- 0.5kW;
Moment of inertia: 2.06 kg/m^2;

Table 1 – Specifications of the engine tested. From [1].

Brand	**Cummins**
Model	ISLe T450 HPCR
Type	Diesel 4 stroke
Fuel	Diesel
Number of cylinders	6, in line
Capacity/ diameter/ course	8 900 cm^3/ 114 mm/ 144.5 mm
Maximum power	335 kW, at 2 200 rpm
Maximum torque	1 627 Nm, at 1 300 rpm
Compression ratio	16.6 : 1
Valves per cylinder	4 (2 admission, 2 exhaust)
Admission	Turbocharged with after-cooler
Idle speed	700 rpm (no load applied)

The central control unit is the Tornado PC (with the Tornado software, version 4.0, Build 335.46 installed), having the following main functions: provide a graphic interface between the user and the test bench, control all the other system components, configure the system and save the data.

The test bench is equipped with an AVL Fuel Balance, which is the fuel temperature and consumption measuring device. The consumption is measured athwart the time corresponding to the variation of the recipient weight. The associated error is of 0.1%.

Three fuels were used on the tests: normal diesel fuel, JP-8 and JP-8 treated with viscosity and cetane improver (JP-8+). The relevant parameters were determined in laboratory by the company Saybolt approved by IPAC (see Table *2*).

Table 2 – Properties of the three fuels used.

Prop.	**Method**	**Diesel**	**JP-8**	**JP-8+**
Density	EN ISO 12185/ ASTM D 4052	0.8322 kg/dm^3	0.7914 kg/dm^3	0.792 kg/dm^3
Kinematic viscosity	EN ISO 3104/ ASTM D 445	2.857 mm^2/s	3.271 mm^2/s	3.541 mm^2/s
Cetane number	EN ISO 5165/ ASTM D 613	54.1	45.7	51.8
Sulfur content	ISO 13032/ ASTM D 4294	0.0818% mass (81.8 mg/kg)	0.141% mass (141 mg/kg)	0.132% mass (132 mg/kg)

The method used for measuring the kinematic viscosity requires a temperature of 40ºC for the diesel fuel, while the method used to determine of the kinematic viscosity of the treated and normal JP-8 fuel requires a temperature of -15ºC. With such temperature difference, it is not surprising to find that the JP-8 (normal and treated) shows a higher kinematic viscosity.

The method used to carry out the tests and consequently the collection of data and samples was as follows:

1. Assembly of the Power Pack on the test bench: for logistical reasons, the engine was not tested isolated, but is framed in the Power Pack, measuring torque and power at the output of the gearbox, not the crankshaft (the gear relation is kept on a 1x1 relation);
2. Accomplishment of the acceptance protocol;
3. Collection of a sample of engine oil;
4. Carrying out the full load tests with diesel fuel:
    - The idle of this Cummins engine occurs at 700 rpm. Since the normal operating regime of this engine occurs near 1200 rpm, this was the lowest rotation speed tested. With 100 rpm intervals (keeping the speed of rotation fixed), the engine has been subjected to the maximum torque that it is capable of withstanding, positioning the accelerator at its' maximum position and measuring the power and torque charged, as well as the bsfc;
5. Carrying out the tests for drawing the performance chart for diesel fuel;
    - Beginning with a torque of 100 Nm, the rotation speed is increased in intervals of 100 rpm, starting at 1200 rpm and finishing at 2200: for each interval, the brake specific fuel consumption and hourly consumption measurements are taken. Once the maximum rotation speed of this torque has been reached, the load is increased in 100 Nm;
6. Collecting a sample of engine oil (20 cl);
7. Collecting a sample of fuel inside the tank;
8. Replacement of fuel (Diesel by JP-8 simple) in the tank;
9. To avoid mixtures of fuels, the engine is left to work for 5 min with weak requests;
10. Repetition of point 4 with JP-8;
11. Repetition of point 5 with JP-8;
12. Repetition of point 6 with JP-8;
13. Collecting a sample of JP-8;
14. Introduction of additives in the JP-8 tank:
    - Carried with sterile syringes and in the following proportions: 0.12% of 2-ethylhexyl Nitrate and 250 ml / 250 l of fuel of Performance Formula viscosity improver of the Stanadyne brand, manufactured by the same American manufacturer of nitrate of 2-ethylhexyl, used by Labeckas et al [3] and [4], Sigma Aldrich. The mixing was done by the test bench mixing system itself; the proportion used is also used by the mentioned authors;
15. Repetition of point 4 with treated JP-8;
16. Repetition of point 5 with treated JP-8;
17. Repetition of point 6 with treated JP-8;

At the end of the tests, the three fuel samples were sent to Saybolt Laboratory, where the density, kinematic viscosity, cetane number and sulfur content were determined; as well as the oil samples, in order to determine an increase of sulfur content in the engine oil. These oil samples were delivered to the laboratories of the Air Base 6 (belonging to the Portuguese Air Force), with the purpose of measuring the engine wear, through the spectrograph of the diluted metals in the oil samples.

RESULTS AND ANALYSIS

The accomplishment of the Power Pack acceptance protocol is an indicator of the engine capability, and means that it can be tested as specified in the technical manuals of the vehicle to which the equipment belongs.

The results of the full load tests allowed to compare the performance of the engine when fed by the three fuels (diesel, untreated JP-8 and treated JP-8).

In terms of extracted torque, the differences between the three fuels are far from significant (Figure 1). The treated JP-8 was the fuel for which it was possible to extract greater torque over the entire range of tested rotational speeds, with diesel being the fuel with the worst performance among the three fuels, dispite the results obtained by Nelson Garcia [2] with a two-stroke engine, in which the JP-8 and diesel achieved the same performance up to 1400 rpm, and the treated JP-8 was able to extract more torque up to 1400 rpm. In the same study, from 1400 rpm up to 2800 rpm, diesel was the one fuel extracting more torque. It would also be expected that the performance of the untreated JP-8 would being worse at high rotational speeds, since it is the fuel which has a considerably lower cetane number compared to the other two fuels, as suggested by Labeckas et al [3], since high rotational speeds will increase the effect of lower cetane number and ignition delay.

Figure *2* shows that the extracted power at the transmission gear is lower for diesel than for the other two fuels, over the full range of tested rotational speeds. In second place was the JP-8, and the one that displayed greater power output was the treated JP-8. This is unlike since the technical manuals of the vehicle, state that the replacement of diesel by the JP-8 might result in maximum 10% power loss. No loss was recorded, but at 1900 rpm the three fuels had the same amount of power charged. Instead of a verified power loss, it was obtained a better performance using JP-8 (either simple and treated), among torque and power, comparing with normal diesel fuel.

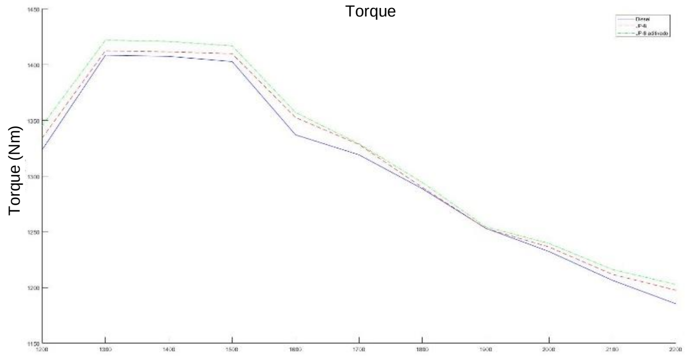

Figure 1 – Full load curves (torque).

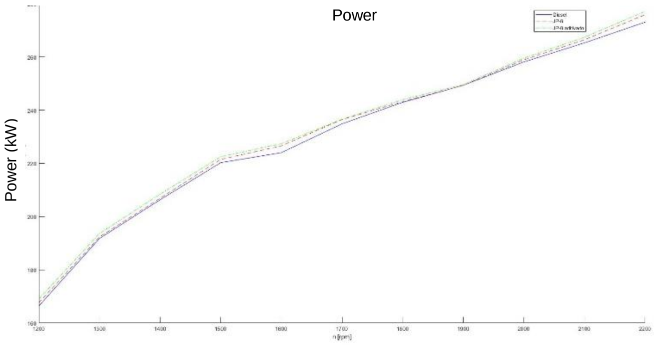

Figure 2 - Full load curves (power).

One explanation for the good results obtained can be the high injection pressures used by the High Pressure Common Rail system present in this engine, as well as the maximum load condition, as stated in [3]. Lee and Bae [4] suggest that the use of high injection pressures contributes to the reduction of ignition delay effects caused by the lower cetane number.

The reduced relevance of the chemistry properties of the fuel will emphasize the physical ones, since the use of high injection pressures will contribute for a better atomization and vaporization of fuel droplets introduced inside the combustion chamber.This will enhance the mixing of the fuel vapor with the air, leading to a major part of the combustion taking place as premix flame rather than diffusion one [5].

On the other hand, the fact the engine is being turbocharged with after-cooler, contributes with pressure increase inside the combustion chamber, leading to the softening of the cetane number effect. The high engine cylinder capacity leads to higher pressures and temperatures and also promotes a better atomization, vaporization and consequent mixture of the fuel inside the combustion chamber.

Untreated JP-8 revealed an increase in torque and power in all range of tested rotational speeds, with exception of 1900 rpm, showing here a decrease of 0.02% with respect of 1253.29 kW and 249.37 Nm of normal diesel fuel, respectively. The highest increase in these two parameters occurred at 1600 rpm with an increase of 1.16% for torque and 1.14% of power against the 1337.07 Nm and 224.04 kW, respectively of diesel. Treated JP-8 showed a better performance on all rotational speed range. The highest increase was observed at the lowest rotational speed tested (1200 rpm) revealing an increase of 1.63% with respect of the 1323.45 Nm of diesel, and 1.57% for the respective diesel power output of 166.37 kW for diesel.

The brake specific fuel consumption (bsfc) of the three fuels at maximum load conditions is shown in Figure *3*. The one fuel showing higher bsfc is the normal diesel fuel. AT 1200 rpm this one shows a bsfc of 243.24 g/kWh, decreasing to the minimum value of 234.56 g/kWh, at 1300 rpm. Between 1300 rpm and 1500 rpm it keeps almost a constant bsfc, increasing only to 236.35 g/kWh at 1500 rpm. From this rotational speed on, it will increase to its

maximum value of 264.28 g/kWh at 2200 rpm. These comparisons are plausible because all of them are higher than the uncertainty presented by the measuring equipment (0.1% on the bsfc).
Since diesel fuel presents a lower Lower Heating Value than JP-8 (simple and treated) [4] it is expected to find a higher bsfc presented by the normal diesel fuel.

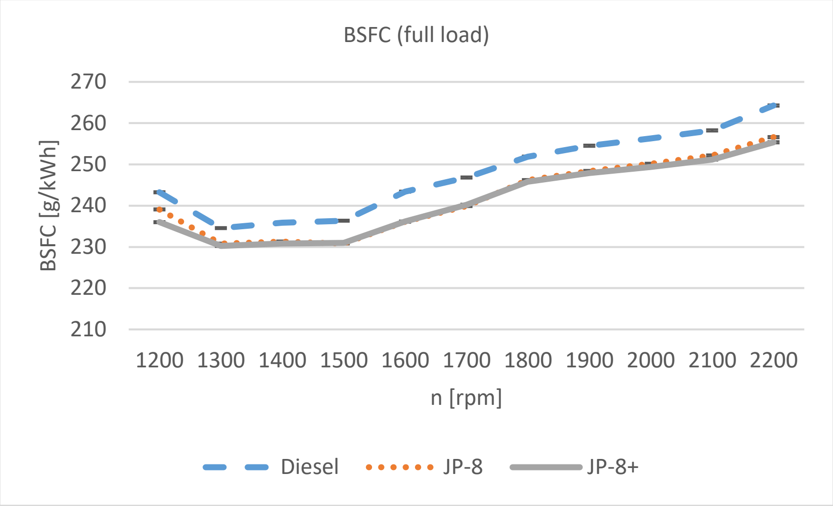

Figure 3 – BSFC at full load.

Both untreated JP-8 and treated JP-8 show a similar behavior of bsfc. Untreated JP-8 presents a value of 239.09 g/kWh at rated 1200 rpm. This value sharply decreases at 1300 to 230.81 g/kWh, its' minimum value registered. Also untreated JP-8 bsfc maintains an almost constant behavior between 1300 and 1500 rpm, here with a value 230.82 g/kWh. From this point on, its' bsfc will increase up to 256.61 g/kWh at 2200 rpm.

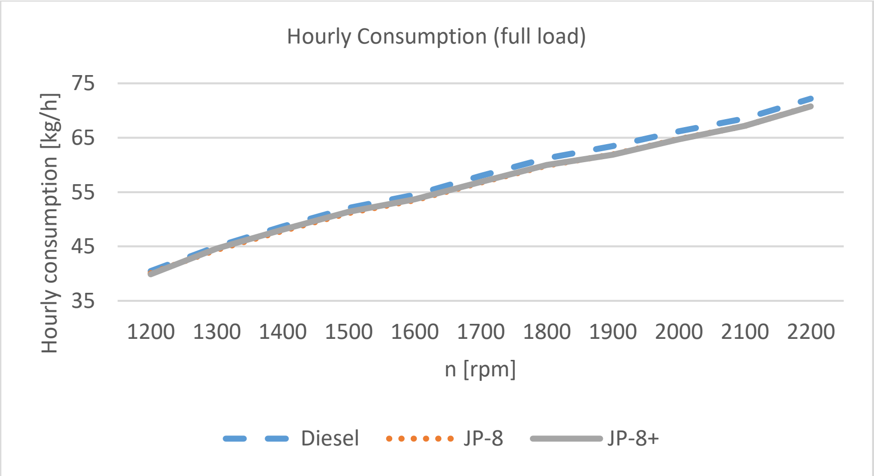

Figure 4 – Hourly consumption at full load.

Treated JP-8 shows a bsfc of 235.99 g/kWh at 1200 rpm. It decreases to its' minimum value of 230.24 g/kWh at rated 1300 rpm, remaining almost constant between this point and the 1500 rpm, here with a value of 230.94 g/kWh. Here on, the value of treated JP-8's bsfc increases to the maximum value of 255.36 g/kWh at 2200 rpm. These results only partially meet the stated in [5], since the pointed study states that JP-8 presents higher bsfc, submitting the engine to full load, in mid rotational speeds. At high rotational speeds, JP-8 should present higher bsfc due to the lower cetane number, which didn't happen in these tests.

Figure 4 shows the evolution of hourly consumption of the three tested fuels, with respect to increase of the rotational speed. For all fuels there is a constant increase of hourly consumption, regarding the increase of the rotational speed. At rated 1200 rpm, diesel fuel, untreated JP-8 and treated JP-8 present hourly consumption of 40.47 kg/h, 40.07 kg/h and 39.88 kg/h, respectively, increasing these values to 72.18 kg/h, 70.80 kg/h and 70.76 kg/h at maximum rotational speed of 2200 rpm.

The more significant reductions of hourly consumption occurred at 1900 rpm for both JP-8 fuels comparing with normal diesel fuel, showing a decrease of 2.42% and 2.52% for untreated JP-8 and treated JP-8, respectively, against the 63.47 kg/h of diesel fuel.

The consumptions were also evaluated keeping constant two rotational speeds (1400 and 2000 rpm), varying the load applied (figures 4 to 8). None of both, untreated and treated JP-8, reveled a higher or lower bsfc, contrary to the stated in [5], at mid rotational speeds (here considered at 1400 rpm), at both low or high loads.

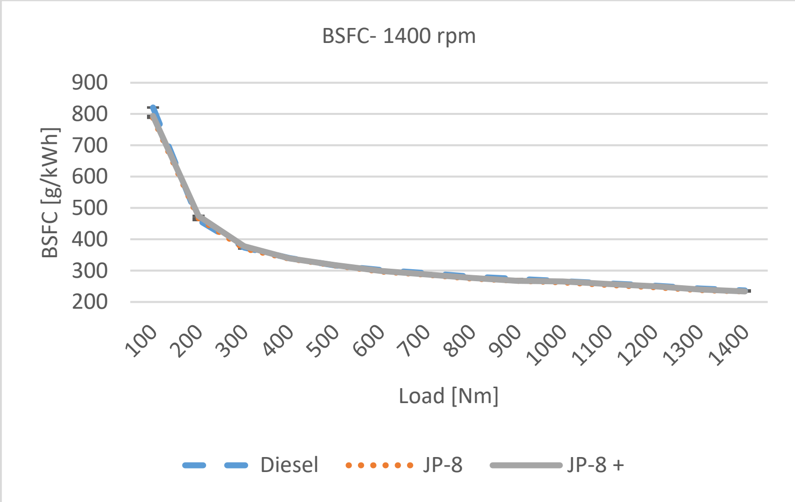

Figure 5 - BSFC for the three fuels (1400 rpm)..

The author in [5] refers that at rotational speeds of this range (1400 rpm), the cetane improver shall induce an increase in the bsfc, although the tests carried by this author were conducted with a smaller naturally aspirated engine, which is expected to decrease the performance of the engine.

The bsfc of untreated JP-8 decreased relatively to the normal diesel fuel, with exception to the 200 Nm and 500 Nm loads, where JP-8 has shown an increase in this parameter of 1.35% and 0.18% with respect to 461.55 g/kWh and 316.03 g/kWh of diesel, respectively.
Among all the other loads tested, the bsfc of untreated JP-8 decreased, showing its maximum decrease of 3.99% for loads of 100 Nm required. The hourly consumption was smaller than the normal diesel fuel, having the higher reduction of 2.28% of the 11.89 kg/h of diesel fuel at 100 Nm.

Also the treated JP-8 revealed a decreasing tendency of the bsfc in almost all of the tested loads, rated at 1400 rpm, with exception of 200 Nm, 300 Nm and 500 Nm, where it was registered an increasing of the bsfc of 2.97%, 1.15% and 0.41%, comparing to the 461.51 g/kWh, 373.94g/kWh and 316.03 g/kW, respectively obtained for normal diesel fuel.

The hourly consumption of treated JP-8 also decreased comparing to the diesel hourly consumption, except on the loads where the bsfc was also higher (200 Nm, 300 Nm and 500 Nm), increasing 0.35%, 0.59% and 0.1%, respectively to the 13.81 kg/h, 16.45 kg/h and 23.2 kg/h consumed by the normal diesel fuel.

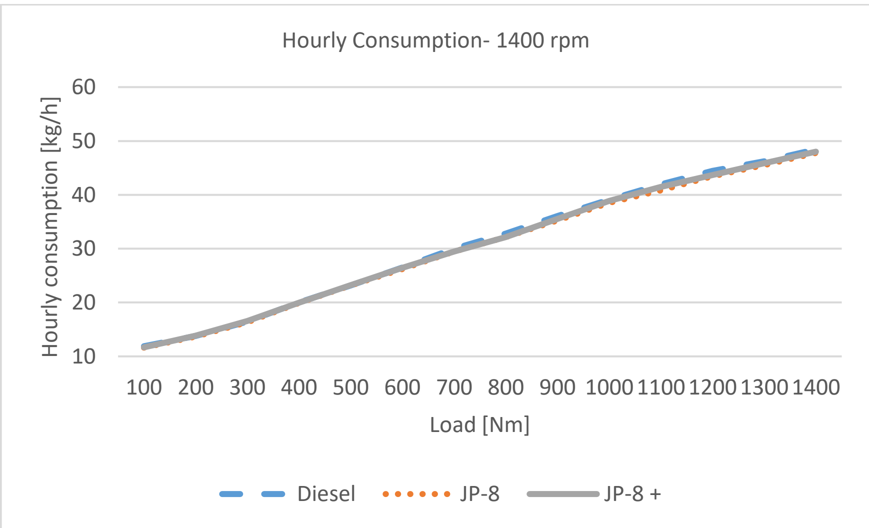

Figure 6 - Hourly consumption of the three fuels (1400 rpm).

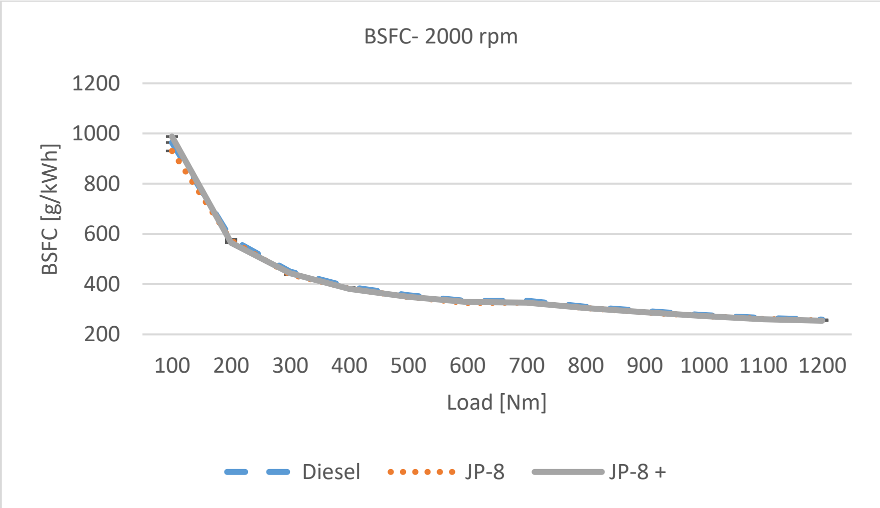

Figure 7 – BSFC for the three fuels (2000 rpm).

At 2000 rpm, untreated JP-8 presented a bsfc reduction (comparing with the normal diesel fuel). The biggest reduction of bsfc at 2000 rpm occurs at the lowest load imposed, 100 Nm, with a reduction of 3.47%, comparing to the 964.41 g/kWh consumed by the normal diesel fuel. Treated JP-8 revealed an increasing of 2.46% comparing with the normal diesel fuel at the same 100 Nm. At the remaining tested loads, treated JP-8 revealed a lower bsfc than the diesel fuel. The highest reduction was of 2.71% of the 580.05 g/kWh consumed by the normal diesel fuel.

The hourly consumption of untreated JP-8 raised 0.2% against the 20.41 kg/h presented by the normal diesel fuel at 100 Nm. From then on, until the 1200 Nm, one could observe a lower hourly consumption of this fuel comparing to diesel fuel. The highest reduction occurred at 900 Nm, representing 2.37% of the 55.56 kg/h of normal diesel fuel. Treated JP-8, revealed no increasing with respect to the diesel fuel, on al tested loads. On all these loads, treated JP-8 presented a lower hourly consumption. The higher reduction occurred at 900 Nm, decreasing 2.35% of the 55.56 consumed by the diesel fuel.

The performance charts for this equipment fed with the three fuels (diesel, JP-8 and treated JP-8 are represented in figures 9, 10 and 11. Only at low loads we can verify the characteristics of Performance charts stated in [6].

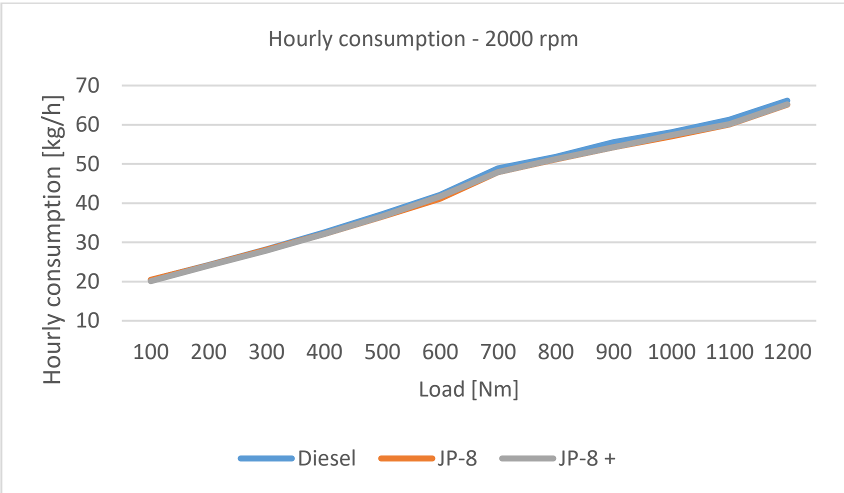

Figure 8 – Hourly consumption of the three fuels (2000 rpm).

It is impossible to determine the bsfc at low rotational speeds because the tests were only conducted from 1200 rpm on, and the engine idling occurs at 700 rpm.
On the other hand, one could expected the close of the bsfc lines before the maximum rotational speed, showing higher bsfc in that region, which also does not happen, because, probably, the manufacturer denotes the 2200 rpm as the maximum rotational speed due to safety reasons in a conservative procedure. At high loads, the bsfc should be higher. Stated by Labeckas et al [5], the increasing loads result in a higher completeness of the combustion process, converting the fuel chemical energy in mechanical energy in a more efficient process.

One simple analysis based on several rotational speeds and loads was performed in order to obtain the volume of fuel spent by the three fuels (Table *3*), thus computing the expenses with each one of these three fuels.

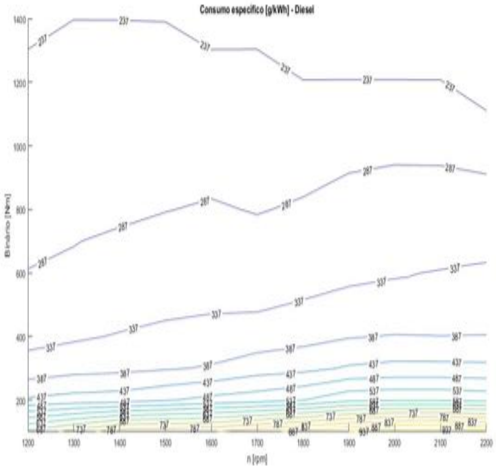

Figure 9 - Performance Chart for normal diesel fuel.

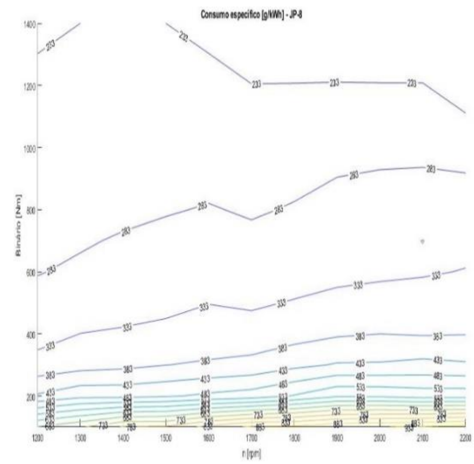

Figure 10 - Performance Chart for untreated JP-8.

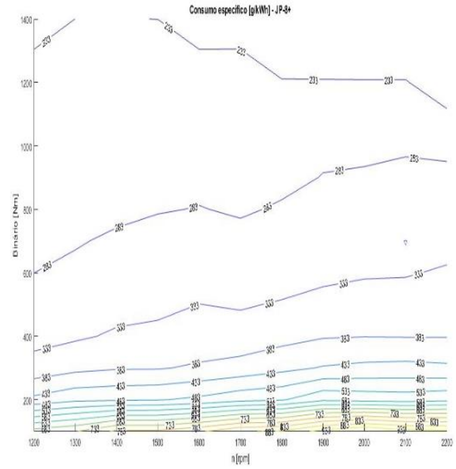

Figure 11 – Performance Chart for JP-8+.

Table 3 – Request for cost analysis applied for the three fuels.

N [RPM]	LOAD [NM]	TIME [MIN]
1200	500	10
	800	10
	1100	10
	Max.	5
1700	500	10
	800	10
	1100	10
	Max.	5
2200	500	10
	800	10
	1100	10
	Max.	5

With the volume of each fuel, calculated based on each fuel density determined in laboratory and the spent mass for each request step, it is possible to obtain the total volume of fuel spent. The shown request in Table *3* would result in consumption of 91.3 dm^3 of diesel, 93.8 dm^3 de untreated JP-8 and 96.4 dm^3 de treated JP-8. Regarding the prices of each fuel 1.16 €/dm^3, 0.545 €/dm^3 and 0.98 €/dm^3 for the normal diesel fuel, untreated JP-8 and treated JP-8, respectively, the total amount spent in this request would be 126.116 € for the normal diesel fuel, with untreated expending 52.6% less of the diesel expenses and treated JP-8 with a reduction of 19.19% of the same value.

Taking into account the volume spent per each fuel, by submitting the engine to the same request with the three fuels used, one can say that 1 dm^3 of diesel equals 1.03 dm^3 of untreated JP-8 and 1.04 dm^3 of treated JP-8. Analyzing the traveled kilometers in 2017 of 39 VBR Pandur II 8x8, randomly chosen, the fuel spent for these 39 vehicles, and having the mean consumption as reference (1.04 dm^3/km), the direct replace of diesel fuel by untreated JP-8 would represent a saving of 27 565€ and savings of 14 000€, if that replacement was done with treated JP-8.

Table 4 – Percentage in mass sulfur content of the engine oil.

	INITIAL SAMPLE	DIESEL	JP-8	JP-8+
% SULFUR MASS	0.99	0.99	0.99	1

The analysis of the sulfur content in the engine oil (Table 4) revealed an increase of this parameter of 0.01% within 6 hours (a short time period) of the engine running with JP-8 (untreated and treated). This duration is not significant enough to measure any result for sulfur in the oil. However, it is also important to note that only 6 hours of work using JP-8 (untreated and treated) were enough to cause a 0.01% increase in the sulfur content in the oil. This might occur due to the high sulfur content present in the fuel, which may pass to the engine oil with the pistons' movement. One way to overcome this problem is to use a more basic oil that neutralizes the acidity caused by the presence of sulfur diluted in the oil.

The analysis of the metals diluted in the oils was inconclusive thus it won't be presented.

CONCLUSIONS

The maximum load tests demonstrated that the tested engine presents a better performance when fed with untreated and treated JP-8 than the normal diesel fuel. The only case this was not verified was at rated 1900 rpm, where untreated JP-8 revealed a 0.02% decrease of torque and power, with respect to the 1253.9 Nm and 249.37 kW, respectively, obtained with the normal diesel fuel. It might be expected that the increase of the rotational speed would result in a higher effect of the cetane number effect, which did not occur at maximum load, maybe due to the high injection pressures induced by the High Pressure Common Rail system equipping this engine, superposing the physical properties of the fuel to the chemical ones.

At maximum load conditions, untreated JP-8 presented a maximum increase of 1.16% and 1.14% of torque and power, with respect to the 1253.9 Nm and 249.37 kW, respectively, extracted from the normal diesel fuel. The lowest increase for treated JP-8 occurred at rated 1900 rpm with an increase of 0.1% and 0.09%, respectively, of 1253.29 Nm and 249.29 kW of normal diesel fuel. Its higher increase was of 1.63% and 1.57%, comparing the values of 1323.45 Nm and 166.37 kW of normal diesel fuel, respectively.

Under variable loads, no significant difference was found between the bsfc among the three tested fuels, at mid rotational speeds (1400 rpm). Under the same conditions, the hourly consumption revealed to be slightly higher for the diesel fuel from the 700 Nm on. The highest difference at this rotational speed occurred at 1200 Nm and consisted of 2.28% and 1.74%, for untreated and treated JP-8, respectively, compared to the 44.47 kg/h presented by the diesel fuel.

At high rotational speed (2000 rpm), the behavior of both untreated and treated JP-8 was very similar, with the exception for very low loads, where, despite the fact of treated JP-8 revealing an increasing of bsfc, untreated JP-8 decreased 3.47% concerning the 964.41 g/kWh presented by the normal diesel fuel.

Due to the lower density, even revealing a lower brake specific and hourly consumption in terms of mass, untreated and treated JP-8 will always present higher volumetric consumptions.

The performance charts demonstrate the most economical operating regime of the tested equipment (in mass consumption per work produced) happen at high loads (from 1000 Nm on), on all the range of rotational speeds tested, until the maximum one (2200) pointed by the manufacturer. In case of 800 to 1000 Nm requested, the rotational speed shall be inside the range of 1200 and 1600 Nm (according to the testes performed).

The sulfur content in the engine oil, in percentage of mass, raised at the end of the performed tests, which might be a factor of premature wearing, since the acidity increase due to the presence of this component will promote corrosion of the metallic equipment lubricated by the engine oil. This might be avoided using a more basic oil.

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