HEAVY-DUTY DIESEL ENGINE CYLINDER LINERS AND PISTON RINGS EXPOSED TO B15 BIODIESEL

Autor
Sérgio Salsamendi

Autor
André Luiz Klemes Bacco

Autor
Dr. Giuseppe Pintaude, Dr. Tiago Cousseau, MSc. Marina Vasco, Heloisa Moreira

ABSTRACT

Looking for friction reduction as a strategy to reduce fuel consumption and exhaust emissions, two research lines are presented: i) one aims to compare two different contact area geometries between twin land oil control ring (TLOCR) and cylinder bore for different normal loads and cylinder liner surface finishing. A universal tribometer with a reciprocating module was employed with loads of 28 and 86 N, frequency of 15 Hz, and constant oil temperature of 90 °C for two hours. Six evaluations were made for each system. Each cylinder liner sample was characterized before and after the wear tests in an optical interferometer. Oil analysis was performed using ferrography and particle counting. ii) the second one also uses the same tribometer and reciprocating module, but with a load of 170 N, frequency of 10 Hz, and only the rougher cylinder liner from the previous study with the top compression ring of the first channel (TR) instead of the scraper ring (TLOCR) and the same interfacial element with contamination of 5% biodiesel B15.

Keywords: Biodiesel B15, Tribological Tests, Lubricants, Friction Coefficient, Wear, TLOCR, Lubrication Regimes.

CILINDROS E ANÉIS DE UM MOTOR DIESEL PESADO EXPOSTOS AO BIODIESEL B15.

RESUMO

Na busca por redução de atrito como estratégia para consequente redução de consumo e emissão de poluentes, duas linhas de pesquisa são apresentadas. i) uma das linhas tem o objetivo de apresentar uma avaliação do comportamento tribológico de dois sistemas anel TLOCR - cilindro variando a geometria da área de contato dos anéis TLOCR (twin land oil control ring) além da força normal de contato entre estes anéis e camisas de cilindros e da rugosidade das camisas de cilindro. Foi utilizado um tribômetro universal com módulo do tipo reciprocating, com cargas de 28 e 86 N, frequência de 15 Hz e temperatura de óleo mantida constante a 90 °C, por duas horas de duração. Foram feitas 6 avaliações para cada sistema. Cada amostra de camisa de cilindro foi novamente avaliada em interferômetro óptico para determinação do desgaste da pista de deslizamento. Análise de óleo foi por ferrografia e contagem de partículas. ii) a segunda linha de pesquisa usa o mesmo tribômetro e módulo reciprocating, porém com carga de 170 N, frequência de 10 Hz e a camisa de cilindro mais rugosa do trabalho anterior com o anel de compressão do primeiro canalete (TR) ao invés do anel raspador (TLOCR) e o mesmo elemento interfacial com contaminação de 5% de biodiesel B15.

Palavras-chaves: Biodiesel B15, Ensaios Tribológicos, Lubrificantes, Coeficiente de Atrito, Desgaste, TLOCR, Regimes de Lubrificação.

INTRODUCTION

There are many paths to meet legal emissions demands looking to reduce environmental impacts generated by the transport sector. Some alternatives being studied will be presented here, like alternative fuels using renewable energies and the improvement of existing heavy-duty engine technologies, with this purpose.

B15 BRAZILIAN DEMAND - biofuel has been classified as renewable source of energy, and its use is increasing significantly worldwide. The usage of biodiesel achieves many world regions. Its leading producers and consumers are the United States of America, Brazil, Germany, Indonesia, Italy, France, Malaysia, and European countries, producing globally per year 28 billion liters, according to British Petroleum, 2018 [1]. According to ANP (Agência Nacional do Petróleo, Gas natural e Biodiesel), the Brazilian allowed monthly production capacity of biodiesel is 700 thousand m³, while the significant production is of 470 thousand m³. This will cover de expected demand for 2023 when B15 (diesel with 15% of biodiesel) will be introduced to diesel engines attending CONAMA PROCONVE P8 (almost the same legal demand of Euro 6 step E) [2].

BIODIESEL EFFECTIVENESS – According to Gaurav et al. (Nov. 2016) [3], biofuels are the most efficient and effective form of renewable energy. They can easily be extracted from biomass, are biodegradable, and environmentally friendly. Its combustion is remarkably similar to fossil fuels, producing fewer toxic components [4, 5]. However, according to Thiyagarajan et al. (2017) [6], points out the carbon dioxide absorbed from the atmosphere by the biomass will be rereleased during its usage. However, the quantity of carbon dioxide returned to the atmosphere is lower than the biomass absorption.

HEAVY-DUTY DIESEL ENGINE EFFICIENCY - Holmberg et al. (2014) [7] evaluated four types of diesel vehicles, its global quantities, its energetic consumption related to cooling (20%), exhaustion (30%) and mechanical work (50%), as well as the losses in those energetic machines. The more significant energy losses were due to friction (33%), being the engine responsible for 7.3 % of those. Inside the engine, the significant friction loss contribution comes from the power cylinder unit (PCU), representing a range of 45 up to 55% [8]. This is well depicted in Figures 1 and 2.

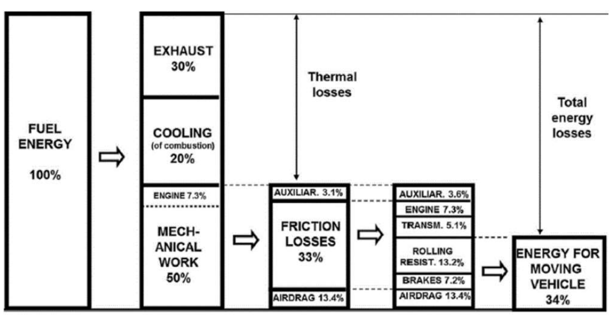

Figure 1 – Busses and Trucks engines energetic consumption average. Source: HOLMBERG et al. (2014).

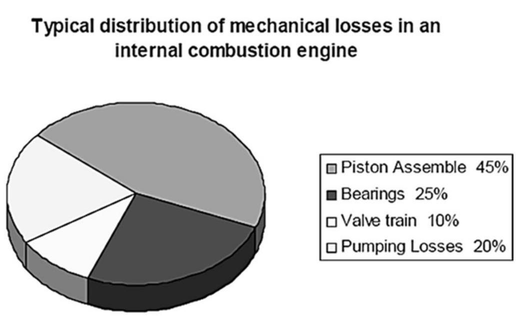

Figure 2 – Internal combustion engine mechanical losses distribution. Source: DOWSON (1993).

Within the piston assembly, the contact between TLOCR and cylinder liner is responsible for 69% of mechanical losses due to friction. In comparison, the top ring (TR) contributes to 23%, as shown in Figure 3.

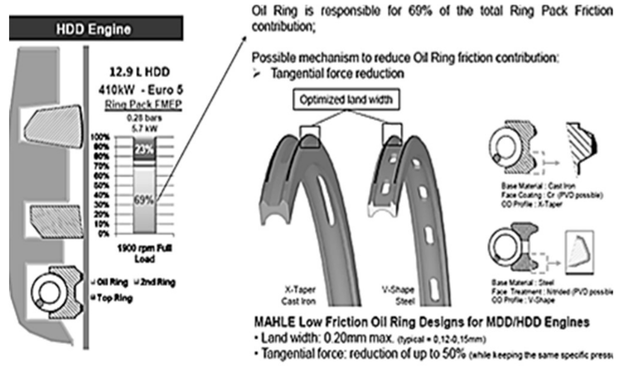

Figure 3 – TLOCR contribution to Heavy-Duty Diesel Engine to friction reduction. Source Mahle do Brasil, (2017).

MATERIALS AND METHODS

Four different tribological systems were used to evaluate friction and wear on heavy-duty internal combustion Diesel liners. Those systems are described below and summarized in Table 1.

Table 1 – Tribological system configuration

Name	Cylinder Liner	Ring	Lubricant	Stroke [mm]	Frequency [Hz]	Temperature [°C]	Load [N]	Test Duration [h]
A	Eu6 pn 21334768	TLOCR V-shape	10w30 A PI CK-4	5	15	90	28	2
B	Eu5 pn 20852790	TLOCR X-Taper	10w30 A PI CK-4	5	15	90	86	2
C	Eu5 pn 20852790	TR	10w30 A PI CK-4	10	10	90	170	2
D	Eu5 pn 20852790	TR	10w30 A PI CK-4 5% B15	10	10	90	170	2

SAMPLES – Cylinder Liner samples were cut from the middle stroke region of two different new cylinder liners. One was manufactured according to the Eu6 standards (smoother) and the other one according to the Eu5 standard (rougher). TLOCR samples were taken from two different new rings, the V-shape with a shorter contact area than X-Taper. Top Ring samples were taken from a new ring. Fourteen lubricant samples were taken from a fresh oil grade 10w30 according to quality API CK-4, one of the samples was mixed with B15 biodiesel, according to ANP n° 45 resolution of 25/08/2014 [9].

EQUIPMENT – all tests were conducted in the CETR-UMT – Bruker (Comprehensive Materials Testing for Mechanical Tribological Properties) at UTFPR (Universidade Tecnológica Federal do Paraná), using the same testbed and support facilities (Figure 4). In contrast, the in-house manufactured samples support holders are showed in Figure 5.

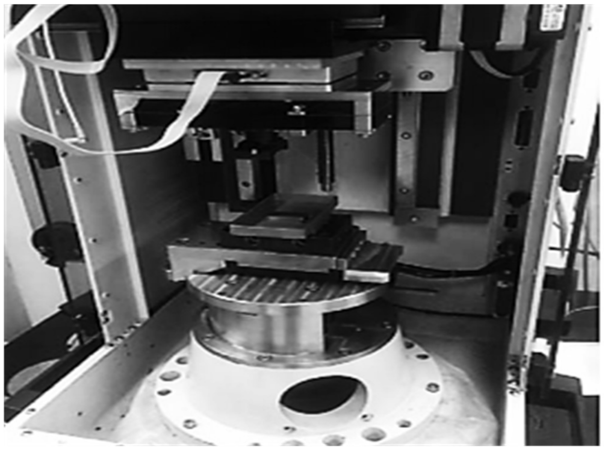

Figure 4 - CETR-UMT – Bruker (Comprehensive Materials Testing for Mechanical Tribological Properties) – UTFPR, LASC.

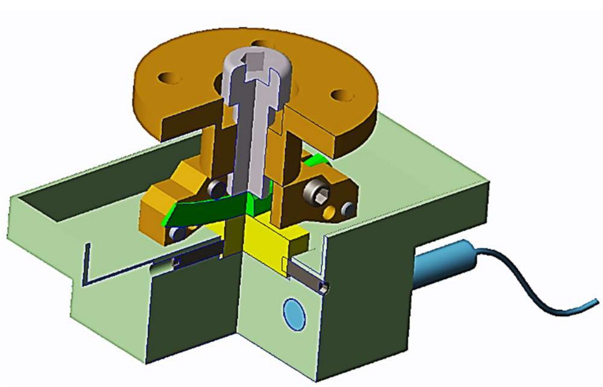

Figure 5 – Tribometer samples support devices and heating resistance.

CHARACTERIZATIONS – Cylinder Liners' roughness was assessed by 3D interferometer at UTFPR before and after tests in the whole 12 mm length of the concave center of each sample, as shown in Figure 6. Special attention was given to height parameters, as other authors have done [10-11]. Lubricant particle counting and iron-graph were performed at PETRONAS after each sample test to characterize wear severity and mechanisms. Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM-EDS) of the cylinder liner samples was also evaluated before and after the test to better understand wear mechanisms tribofilm formation.

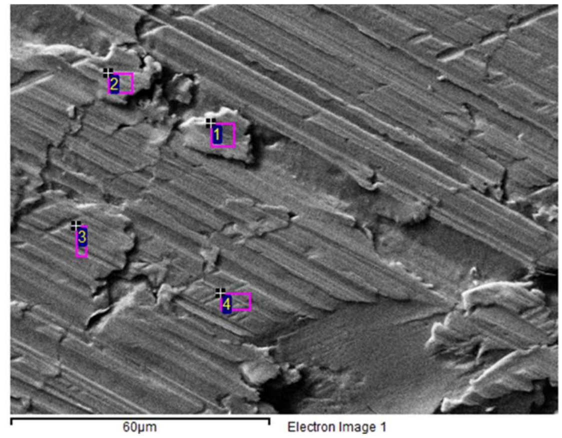

Figure 6 – SEM-EDS characterization four points of evaluation to create the statistical average

RESULTS

ROUGHNESS PREVIOUS AND AFTER TEST – the cylinder liner samples had its roughness evaluated before and after the tribological test using an optical interferometer from Taylor Hobson. As usual for its characterization, the Abbott Firestone curve (Ssk, Sku, Sk, Spk, Svk, Srm1, and Smr2) along with some volume parameters (Vvv and Vmp) were investigated. For the tribological systems A and B, each parameter's average and standard deviation are shown in Tables 2 and 3 for the unworn and worn surfaces, respectively. The percentage variation between unworn and worn surface roughness is given in Table 4.

The tribological systems C and D are presented in Tables 5, 6, and 7, showing the average and standard deviation of the same parameters presented before, for systems A and B. Table 5, shows the values before the tribometer tests and Table 6, the same parameters after the tribometer test. . The variation, in percentage, between the samples before and after the tribometer test, are presented in Table 7.

Table 2 – 3D Interferometer results before the tribological test for systems A and B

Roughness parameters	Cylinder Eu6 pn		Cylinder Eu5 pn	
	Average	Standard Deviation	Average	Standard Deviation
Ssk	-2.3227	0.2300	-2.0595	0.3155
Sku	10.9443	1.7749	10.2410	2.6601
Sk [um]	0.9148	0.0226	1.0994	0.0934
Spk [um]	0.3950	0.0254	0.5131	0.0600
Svk [um]	1.7708	0.0694	1.8282	0.0993
Sr1 [%]	9.1763	0.3883	9.2357	0.6277
Sr2 [%]	81.3680	0.7681	80.7690	1.2926
Vvv	0.0640	0.1564	0.0002	0.0000
Vmp	0.0000	0.0001	0.0000	0.0000

Table 3 - 3D Interferometer results after the tribological test for systems A and B

Roughness parameters	Cylinder Eu6 pn		Cylinder Eu5 pn	
	Average	Standard Deviation	Average	Standard Deviation
Ssk	-2.5896	0.4466	-2.7914	0.3547
Sku	12.9725	4.2167	15.3694	3.3073
Sk [um]	0.7769	0.0868	0.7772	0.0640
Spk [um]	0.3903	0.0891	0.4097	0.0859
Svk [um]	1.7644	0.1700	1.7570	0.1297
Sr1 [%]	10.1320	1.3684	10.9018	1.7628
Sr2 [%]	81.6486	1.2935	82.7518	1.6575
Vvv	0.0002	0.0000	0.0002	0.0000
Vmp	0.0000	0.0000	0.0000	0.0000

Table 4 - 3D interferometer difference after the tribological test for systems A and B

Roughness parameters	Cylinder Eu6 pn		Cylinder Eu5 pn	
	Average	Evaluation	Average	Evaluation
Ssk	-11%	↗	-26%	↗
Sku	-19%	↗	-33%	↗
Sk [um]	15%	↘	41%	↘
Spk [um]	1%	→	25%	↘
Svk [um]	0%	→	4%	↘
Sr1 [%]	-10%	↘	-15%	↘
Sr2 [%]	0%	→	-2%	→
Vvv	100%	↓	12%	↘
Vmp	56%	↓	30%	↘

For systems A and B, results just from interferometry bring us the following statements. i) there will be friction reduction since valleys are predominant above the median line of Skewness. ii) slice way wear has spread the high distribution of kurtosis. iii) Sk parameter in smoother cylinder liners had less wear than rougher one. iv) higher peaks were less wear in smoother cylinder liners (Eu6), just 1%. Simultaneously, rougher Cylinder Liner (Eu5) decreases 25% of its peaks to the Spk parameter. v) Svk has no significant variation to smoother cylinder liner to its valleys. In comparison, the rougher cylinder liner decreases by 4%. As expected, the valleys area was barely affected due to the mild wear conditions of the tests. vi) in both cylinder liners' samples (Eu6 and Eu5), changes on peaks will modify the Abbot curve in the Sr1 area, almost in the same proportion with more impacted wear to rougher cylinder liners. vii) no significant variation to smother and rougher cylinder liners to modify the Abbot curve in the Sr2 area. viii) Vvv or Dale void volume represents the amount of lubricant the valleys can hold, a significant reduction for the smoother cylinder liner; rougher cylinder liner had just 12%. ix) Vmp or Peak material volume decreased significantly in both cylinder liners, so the material removed from peaks was deposited in the valleys, changing its volume significantly.

Table 5 – 3D Interferometer results before the tribological test for systems C and D

Roughness parameters	Cylinder			
	Eu V Cylinder Liner with 5% B15 dilution in VDS4.5 oil	Eu V Cylinder Liner without dilution in VDS4.5 oil	Average	Standard Deviation
Ssk [um]	0,7477	0,6647	0,7062	0,0587
Sku [um]	55,9500	29,3200	42,6350	18,8303
Sk [um]	0,8922	1,1120	1,0021	0,1554
Spk [um]	1,1990	0,7008	0,9499	0,3523
Svk [um]	2,3350	1,8500	2,0925	0,3429
Sr1 [%]	12,2400	9,1690	10,7045	2,1715
Sr2 [%]	81,6400	80,4200	81,0300	0,8627
Vvv	0,0002	0,0002	0,0002	0,0000
Vmp	0,0001	0,0000	0,0001	0,0000

Table 6 – 3D Interferometer results after the tribological test for systems C and D

Roughness parameters	Cylinder			
	Eu V Cylinder Liner with 5% B15 dilution in VDS4.5 oil	Eu V Cylinder Liner without dilution in VDS4.5 oil	Average	Standard Deviation
Ssk [um]	0,6446	0,8043	0,7245	0,1129
Sku [um]	3,0268	3,3328	3,1798	0,2164
Sk [um]	0,0058	0,0049	0,0053	0,0006
Spk [um]	0,0029	0,0029	0,0029	0,0000
Svk [um]	0,0010	0,0007	0,0008	0,0002
Sr1 [%]	14,6900	18,0100	16,3500	2,3476
Sr2 [%]	95,7900	96,3600	96,0750	0,4031
Vvv	0,0000	0,0000	0,0000	0,0000
Vmp	0,0000	0,0000	0,0000	0,0000

Table 7 - 3D interferometer difference after tribological test for systems C and D

Interferometer difference				
Roughness parameters	Cylinder			
	Eu V Cylinder Liner with 5% B15 dilution in VDS4.5 oil		Eu V Cylinder Liner without dilution in VDS4.5 oil	
	Average	Evaluation	Average	Evaluation
Ssk [um]	14%	↘	21%	↗
Sku [um]	95%	↘	89%	↘
Sk [um]	99%	↘	100%	↘
Spk [um]	100%	↘	100%	↘
Svk [um]	100%	↘	100%	↘
Sr1 [%]	20%	↗	96%	↗
Sr2 [%]	17%	↗	20%	↗
Vvv	100%	↘	100%	↘
Vmp	100%	↘	0%	→

For systems C and D, Ssk (Skewness) is above 0, which means that the height distribution is skewed below the mean plane, Sku (Kurtosis) was much higher than 3, i.e., a spiked height distribution before the tribometer test. After the tests, the number is close to 3, which means that sensitive portions and indented portions co-exists. Sk, or the core roughness of the surface, was drastically reduced after tribometer tests. It was even more reduced for system C or the one without biodiesel dilution. Spk, the nominal height of the material that may be removed during the tribometer test, was reduced to the same values in both systems; Svk, a measure of the valley depths below the core roughness, is also with approximately the same value after the tests and represent a shallower valley than before the tests. Sr1 (related to the peaks) and Sr2 (related to the valleys) are higher after the tests, representing the percentage of the surface that may be removed during running-in. Vvv and Vmp indicate a measure of the surface's void volume between various heights as established by the chosen material ratio values. The Dale Void Volume, Vvv, may be useful in indicating the potential remaining volume after significant surface wear has resulted. It was already low before the tests and kept low after it, or 0.

CYLINDER LINER SEM AND SPECTROMETRY ANALYSIS BEFORE AND AFTER TEST – Both cylinders samples were evaluated with SEM. It is essential to point out test loads are different between smoother (Eu6 – 28N) and rougher cylinder liners (Eu5 – 86 and 170N) and also between rougher cylinder liners, lowest and highest magnifications were used to show the roughness change and wear of sliding surfaces, Figure 7, 8, 9 and 10 show the differences before and after tests from both cylinder liners, taken in the center of each sample.

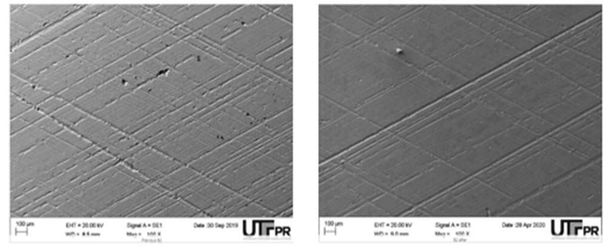

Figure 7 – Surfaces of cylinder liner of system A: before tribotest (left) and after tribotest (right).

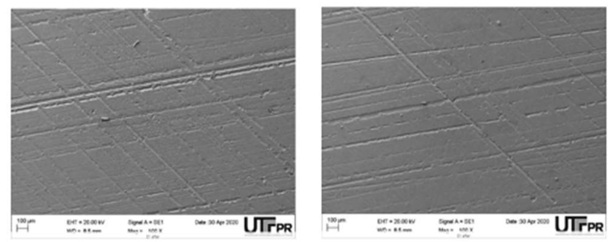

Figure 8 – Surfaces of cylinder liner of system B: before tribotest (left) and after tribotest (right)

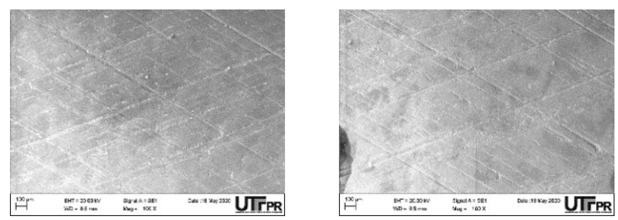

Figure 9 – Surfaces of cylinder liner of system C: before tribotest (left) and after tribotest (right).

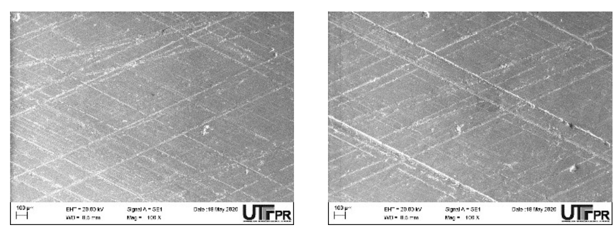

Figure 10 – Surface of cylinder liner of system D: before tribotest (left) and after tribotest (right).

Additionally, EDS evaluation of the cylinder liners' samples surface was performed before and after tribometer'stest, evaluating inside and outside of the sliding surfacein 4 different areas. The processing option with all elements analyzed results in weight%. Five elements chosen for the analysis were based on previous ICP (inductively coupled plasma) characterization of the oil and the known composition of the cylinder liners. From those, the main elements related to the oil additive package (Phosphorus, Sulfur, Calcium, and Zinc) and Iron were chosen for the discussion since they are likely to be the ones related to wear and friction, as usually observed in other researches.

Figure 11 presents the variation in the percentage of the chemical elements presented in the wear track before and after the tribological test on systems A and B to verify if the TLOC ring geometry affects tribofilm formation. Figure 11 also presents the chemical composition of worn surfaces in and out-side the wear track. In these evaluations, i) that the Phosphoric acids used as additives in lubricants to reduce the system friction affect the results after tribotest inside the sliding surface, where Phosphorus has increased weight around 0.7 %. ii) another perception was that Calcium was used as an additive in lubricants with detergent characteristic, used to reduce the lacquer formation and other deposits on PCU surfaces and the formation of acid contaminants due to combustion residues, had increased the weight by around 0.75%. iii) Zinc had a significant increase of 2%; it is a consequence of Zinc di-thiophosphates (ZDDP) applied as an additive to avoid oil oxidation and anti-wear tribofilm formation. iv) Iron has decreased proportionally the gain of other elements in both systems near of - 4%. No significant differences in tribofilm composition were observed among the studied TLOC rings. Also, evaluating inside and outside the wear track on worn surfaces leads to the same conclusions as evaluating unworn and worn surfaces. This indicates the formation of tribofilms due to thermal decomposition is similar to the ones obtained in the rubbing contacts.

The same EDS was performed for systems C and D, after the tribotests, inside and outside the sliding surfaces at four different points. The same five elements were chosen. Figure 12 presents the variation of the elements, inside and outside the systems C and D. For the element Phosphorus, in system C, there is a higher amount inside the sliding surface than outside. This can be explained by the Phosphoric acids used as additives in lubricants to reduce the system friction. For system D, it is possible to conclude that there is much more Phosphorus outside the sliding surface, which is compatible with the amount of biodiesel diluted in oil, which contains P from the animal fat used in biodiesel. Calcium used as an additive in lubricants with detergent characteristic, already explained, has also increased in sliding surface area, for systems C and D. Zinc also had a significant increase for systems C and D, inside the sliding surface area, of around 1.5%. Iron has decreased inside the sliding surface area, which is expected due to other elements' quantity, that increased.

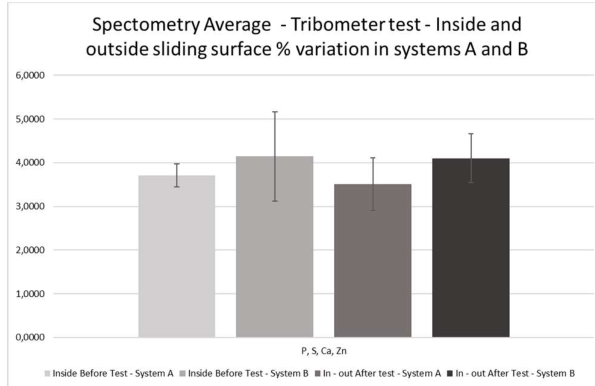

Figure 11 – Spectrometry evaluation cylinder liner Systems A and B comparing after and before tribotest inside the sliding surface.

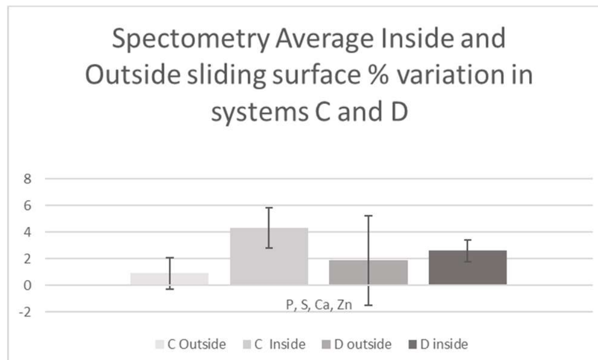

Figure 12 - Spectrometry evaluation cylinder liner Systems A and B comparing after and before tribotest inside and outside the sliding surface.

TRIBOLOGICAL TESTS – systems A and B were tested for 120 minutes using the tribometer CERT-UMT.

Figures 13 and 14 show the average coefficient of friction for every 20 minutes of testing for System A and B, respectively. The system A (CoF average value of 0.110±0.002) presented no significant but better CoF results than system B (CoF average value of 0.111±0.002), at last legs 5 and 6, almost ending the test, with stabilized conditions and after running period, considered here as the first three legs, three variables that justify this CoF reduction, a) the test was performed with 28N load instead of 86N in system B, b) the cylinder liners' roughness in system A is smoother due to parameters as Sk 17% and Spk 25% are lower than system B and c) the TLOCR had its running surface area reduced, approximately 43% due better design.

System C and D were tested for 120 minutes. The friction coefficient tests for System C shows a CoF around 0.121 ± 0.005 all over the tests. For System D, , the CoF was showing a constant behavior and a value around 0,121±0,005. The values, by leg, are shown in figure 15

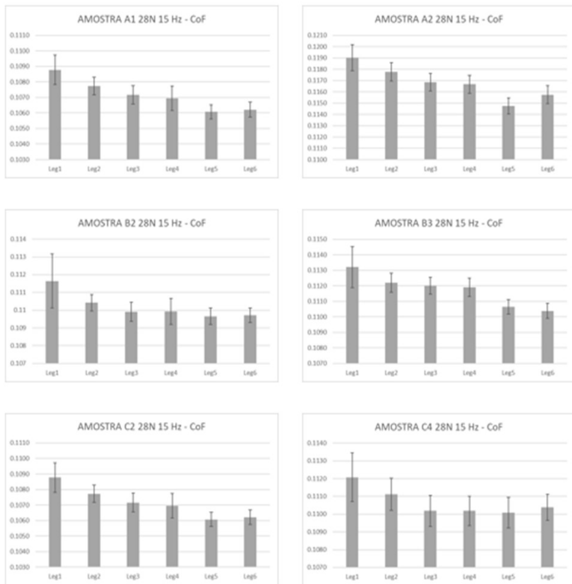

Figure 13 – System A 28N load, 15Hz, 10W30 oil, CoF results

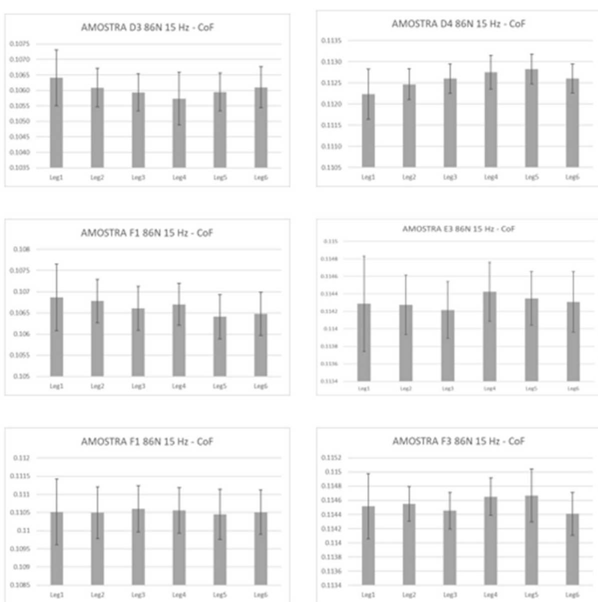

Figure 14 – System B 86N load, 15Hz, 10W30 oil, CoF results

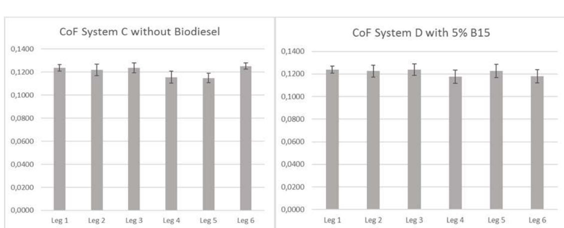

Figure 15: Systems C and D, 170 N Load, 10 Hz, CoF

PARTICLES COUNTING - systems A and B presented almost the same particles counted inside the remaining lubricant after the tribological test. Table 7 presents results from oil samples evaluation using ICP (inductive coupled plasma) comparing the variation of element particles from wear and additives of a new oil sample without using and after tribological tests. It was possible to see that five elements have contributed to particle counting increase after tribological tests on systems A and B; they are Calcium, Phosphorus, Zinc, Tin, and Nickel. The oil additives as Calcium, Phosphorus, and Zinc elements combined with wear particles founded (Tin and Nickel) are responsible for the particle 7% rise. Additionally, soot was equally added after tribological tests on systems A and B, increasing 4 Abs/cm.

For Systems C and D, most of the detected particles are similar to those observed in Systems A and B. However, the high content of Phosphorus and Calcium in System D resulted from the B15 dilution. Both elements are present in biodiesel due to the animal fat used in the process.

TRIBOLOGICAL TEST AND LUBRICANT 100°C KINEMATIC VISCOSITY – possibly due to the short test duration (120 min) was not possible to perceive lubricant viscosity deterioration to both systems A and B. Table 8 shows the results found, due to method accuracy it was not possible to point out a robust conclusion over Cinematic viscosity increase after tests. However, both samples after tests increase the viscosity by 8% to system A and 5% to system B. One of the factors contributing to that was the Nitration (net) increase in 5 and 2 points respectively to system A and B, reflecting the contamination of oil samples, perhaps due to ambient and temperatures test exposition.

For systems C and D, the Kinematic Viscosity has increased in both oil samples. It is even higher for system D. This can be explained by the higher oxidation found in the sample, mainly due to the biodiesel dilution. Biodiesel contains oxides due to its production process. The oxidation increases the viscosity of oil and also leads to a higher wear rate of engine components. It is shown in Table 9.

Table 7 – ICP Oil samples analysis of system A and B compared with the non-used oil sample (zero values were replaced for 0.0001 to avoid mathematical error).

Propriedade Property		Método Method	New VDS-4.5 oil sample (10W-30) API CK-4	System A		System B	
			Tempo de Serviço Time in service 0 h	Tempo de Serviço Time in service 2 h			
			One sample result	Average 6 samples	Difference from new oil	Average 6 samples	Difference from new oil
Desgaste e elementos contaminantes Wear and contaminant elements	Ca	ASTM D5185	2144	2330.0000	8.68%	2318.3333	8.13%
	Mg		9	6.5000	-27.78%	6.5000	-27.78%
	P		709	950.5000	34.06%	946.0000	33.43%
	Zn		1159	1031.6667	-10.99%	1030.0000	-11.13%
	Fe		2.1	2.0000	-4.76%	2.0000	-4.76%
	Pb		1.4	1.1667	-16.67%	1.0000	-28.57%
	Cu		0.1	6.5000	6400.00%	1.1667	1066.67%
	Sn		0.0001	1.0000	999900.00%	1.0000	999900.00%
	Al		1.5	0.8333	-44.44%	1.0000	-33.33%
	Ni		0.0001	0.1667	166566.67%	0.0000	-100.00%
	Si		13	7.6667	-41.03%	8.1667	-37.18%
	Na		3.1	1.8333	-40.86%	1.1667	-62.37%
	Particles Counting [ppm]		**4042.2**	**4339.83333**	**7%**	**4316.33333**	**7%**
Contaminants	Fuligem / Soot	ASTM 2412-10	0.0001	4.0000	3999900.00%	3.6667	3666566.67%

Table 8 – ASTM 445 Cinematic Viscosity@100°C and DIN 51452/ASTM 2412-10 Nitration Oil samples analysis of system A and B compared with non-used oil sample (zero values were replaced for 0.0001 to avoid mathematical error).

Propriedade Property		Método Method	New VDS-4.5 oil sample (10W-30) API CK-4	System A		System B	
			Tempo de Serviço Time in service 0 h	Tempo de Serviço Time in service 2 h			
			One sample result	Average 6 samples	Difference from new oil	Average 6 samples	Difference from new oil
Condição do óleo Oil Condition	Viscosidade a 100°C Viscosity at 100°C	ASTM D445	11.45	12.3560	7.91%	11.9867	4.69%
	Nitração (liq.) / Nitration (net)	DIN 51453 ASTM 2412-10	0.0001	4.6667	4666566.67%	2.1667	2166566.67%

Table 9 - Oil Sample analysis for System C and D

Propriedade Property		Método Method	Método Chevron Chevron Method	New VDS4.5 Oil	System C	System D
				Tempo de Serviço Service Time [h]	Tempo de Serviço Service Time [h]	Tempo de Serviço Service Time [h]
				0	4	4
Desgaste e elementos contaminantes Wear and contaminant elements	Ca	ASTM D5185	Espectométrico - EEO	2100	2250	3430
	Mg			9	13	7
	P			709	922	1030
	Zn			1000	1020	1120
	Fe			2,1	3	2
	Pb			1,4	1	2
	Cu			0,1	1	0
	Sn			0	1	0
	Cr			0	0	0
	Al			1,5	1	1
	Ni			0	0	0
	Si			13	6	7
	Mo			1,7	0	1
	Na			3,1	2	2
	B			0,1	0	0
	Fuligem	ASTM 2412-10	Abs/cm	0,0001	7	4
	Sulfatos / Soot	DIN51452 ou/or TGA	Espectométrico - EEO	0	0	0
Condição do óleo Oil Condition	Viscosidade a 100°C Viscosity at 100°C	ASTM D445	D-445	11,45	12,06	13,47
	Oxidação (liq.) / Oxidation (net)	DIN 51453	Espectométrico - EEO [Abs/cm]	0	0	13
	Nitração (liq.) / Nitration (net)	DIN 51453	Espectométrico - EEO [Abs/cm]	0	3	7

CONCLUSIONS

A series of reciprocating tests was performed to verify the possible friction reductions using different ring geometries and alternative fuel for the Diesel system. Based on the abovementioned results, we can put forward the following conclusions:

SURFACE ROUGHNESS ANALYSIS – For systems A and B, No significant wear on the Spk parameter to smoother Cylinder liner (Eu6); on the other hand, in rougher Cylinder Liner (Eu5), the Spk parameter decreased 25% after reciprocating test. For systems C and D, there was a high and similar wear after the tribometer test, in terms of Sk (core), Spk (peaks), and Svk (valleys).

FRICTION BEHAVIOR – Any significant difference was detected between the friction behavior determined for Systems A and B (average value of 0.111) and Systems C and D (average value of 0.121).

The CoF of systems A and B have almost the same values, around 0.110 (A) and 0.111 (B), demonstrating in this test almost the same friction behavior since the surface roughness difference between systems A and B are not significant too. The CoF of systems C and D have the same values, around 0.121, which shows, during these tests, that the biodiesel dilution of 5% did not affect the friction.

EDS RESULTS AND THE LUBRICANT ADDITIVES - The cause of less tribofilm formation in system A is its lower load and ring geometry in contact area with cylinder liner than system B has.

For system C it is possible to conclude that there is much more Phosphorus outside the sliding surface, which is compatible with the amount of biodiesel diluted in oil contains P from the animal fat used in biodiesel.

PARTICLES COUNTING - systems A and B presented almost the same particles counted, and soot increase inside the remaining lubricant after the tribological test.

For systems C and D, most of the detected particles are similar to those observed in Systems A and B. However, the high content of Phosphorus and Calcium in System D resulted from the B15 dilution

TRIBOLOGICAL TEST AND LUBRICANT 100°C KINEMATIC VISCOSITY – possibly due to the short test duration (120 min) was impossible to perceive lubricant viscosity deterioration to both systems A and B.

For systems C and D, the kinematic viscosity has increased in both oil samples. It is even higher for system D. This can be explained by the higher oxidation found in the sample, mainly due to the biodiesel dilution.

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