Evaluation of thermo-oxidized Jatropha bio-oil in lubrication of actual wet clutch materials

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Abstract

In this work, an assessment of the performance of thermo-oxidated Jatropha oil as a lubricant of actual wet clutch materials was carried out and compared to that of a commercial automatic transmission fluid (ATF). For this purpose, Jatropha oil, a commercial ATF and a blend of 20%vol. Jatropha oil-

80%vol. ATF (B20-ATF) were subjected to thermo-oxidative ageing at 26 and 100°C, followed by pin-on-disk testing with disk samples prepared from an actual wet clutch under boundary lubrication. The changes of film thickness with time at the sliding interface was calculated by considering the effects of squeeze film in the friction material. Changes in oxidation, viscosity and viscosity index of the samples were evaluated along with friction coefficients at sliding speeds between 0.06 and 0.9m/s. Jatropha oil was much more sensitive to thermo-oxidation than ATF and B20-ATF, while B20-ATF was slightly more oxidized than ATF. Jatropha oil and B20-ATF showed a higher viscosity increase than ATF with thermo-oxidation, while the viscosity index of all oils was considerably reduced, being Jatropha oil and B20-ATF the most reduced. Finally, anti-shudder property, as measured by the change in friction coefficient with sliding speed, of Jatropha oil and ATF was improved by thermo-oxidation at 26°C but worsened at 100°C. In the case of B20-ATF, thermo-oxidation did not produce significant anti-shudder property changes for both temperatures. Therefore, the results in this work indicate that using pure Jatropha oil as an ATF would be unsuitable. However, blending ATFs with Jatropha oil in specific proportions may be apposite to improve friction properties of wet clutches even under thermo-oxidative condition, while contributing to environmental protection.

Keywords

Friction coefficient; thermal degradation; bio-oil; wet clutch

1. Introduction

To reduce the negative environmental impact caused by producing, using and disposing of mineral and synthetic oils, vegetable oils have been suggested as promising eco-friendly alternatives for a number of applications including hydraulic fluids [1], drilling [2] and cutting fluids [3] as well as in lubrication for automotive components [4]. As for this last application, good boundary lubrication behavior, low viscosity, high viscosity index and biodegradability are some of the most relevant characteristics found in several bio-lubricants, which may be appropriate for use even in demanding systems as automatic transmissions. Nonetheless, application of vegetable lubricants as automatic transmission fluids (ATFs) has been barely explored.

The first reported experimental study about the examination of vegetable oils as ATFs was reported by Abere et al. [5]. For this, the authors compared different physical properties, namely, viscosity, viscosity index, color, specific gravity, water content, pour point, flash point, etc. of some vegetable oils (coconut, soybean and groundnut and palm oils) with those of a commercial ATF. Overall, they found that groundnut oil was the best option to produce an ATF, since the evaluated properties were very similar to those of the commercial ATF. Later, Farfán-Cabrera et al. [6] reported an approach to the lubrication of an automotive wet clutch using a neat vegetable oil (Jatropha oil) and blends of Jatropha oil with two commercial ATFs in different concentrations. These authors found that the friction coefficients in the wet clutch when using partially or neat vegetable oil were lower than those measured when using commercial ATFs, mainly at low sliding speeds, which may be positive for increasing the lubricant´s anti-shudder property. Wet clutch shudder is produced by undesirable self-excited vibrations caused by stick-slip effects at the plates´ interface [7]. According to the model proposed by Kugimiya et al. [8], shudder occurs when wet clutch friction increases as the sliding speed decreases, so low dynamic friction coefficients at low sliding speeds are suitable to prevent shudder within the ATF service life [8, 9].

The potential and reliable use of neat vegetable oils as ATFs, as well as in other applications, is limited by their significantly poor oxidation stability resulting from their chemical composition based on fatty acids [10]. However, using vegetable oils as additive in certain proportions for improving lubricating properties of mineral or synthetic oils is a suitable alternative for reaching lubricant biodegradability and environmental care in some extent. In general, accelerated oxidation of oil occurs when used at high temperatures, which increases its viscosity and deteriorates its tribological properties. Hence, evaluating the tribological properties of vegetable oils, including the effects of oxidation and other degradation processes occurring in each specific application, is needed to have a better understanding of their performance and wider their scope of applicability. In this regard, there are only a few studies reporting thermal ageing effects of vegetable oils on their tribological performance. Kreivaitis et al. analyzed the oxidation effects of rapeseed oil on friction and wear behavior using a four-ball test [11]. There, the oil was oxidized at a temperature of 100°C in various heating periods up to 40h. These authors found that wear and friction had a great dependency on oxidation time, meaning that longer oxidation periods worsen lubricity in terms of increasing friction and wear. In other research work, Mannekote and Kailas assessed the oxidation effects of soybean, groundnut, rice bran, palm, and sesame oils on their tribological properties by using a four-ball test [12]. The oils were oxidized at different temperatures (60, 80 and 100°C) for 14, 28, and 42 days, respectively. In contrast to results reported in [11], Mannekote and Kailas determined an increase in wear with oxidation temperature and time for all oils studied, but friction coefficients were lower for aged oil samples.

Although the aforementioned studies represent attempts for understanding the oxidation effects of some vegetable oils on their tribological behavior, there are no reports on the effects of oxidized vegetable oils when used as ATFs. Currently, Jatropha oil is considered as one of the most proficient bio-lubricant options for automotive applications, including the engine, gear box and braking [4]. Thus, the purpose of this work was to assess the performance of thermo-oxidated Jatropha oil as a lubricant of actual wet clutch materials and its comparison with a commercial ATF.

2. Experimental details

2.1. Oil samples and thermo-oxidation procedure

A commercial ATF-III, crude Jatropha oil and a blend prepared with 80%vol. of ATF and 20%vol. Jatropha oil (B20-ATF) were tested. The blend was chosen to assess the effect of introducing a crude vegetable oil on the ageing process of the ATF and the resulting friction coefficients of a wet clutch. Besides, it has been previously found that a percentage around 25%vol. of this vegetable oil in fresh ATFs can be effective to reduce friction coefficient and enhance their anti-shudder property [6]. The Jatropha oil tested in this work was well characterized by using ESI Mass spectroscopy [13]. The main fatty acids found were: 32.7% araquidic acid (saturated with long chain), 26.6% linoleic acid (polyunsaturated), 25.2% behenic acid (saturated with long chain) and 11.2% oleic acid (monounsaturated). It has been widely demonstrated that lubricity and thermal oxidation stability of vegetable oils are influenced by fatty acid unsaturation and chain length. So, having oils containing high concentration of saturated fatty acids (low degree of unsaturation) is suggestable for having better lubricity and oxidation stability in vegetable oils [14]. Although it is well known that advanced bio-lubricants are produced with great care to remove any contaminating substances and providing low unsaturation degree through different chemical modifications, namely, transesterification, partial hydrogenation and epoxidation [14], the Jatropha oil used in this work, because of its low degree of unsaturation, was only filtered meticulously and put to the test. It is because adding chemical processes to the bio lubricant production means cost increase and perhaps affectation to the environment.

A laboratory thermo-oxidation ageing process, based on the method for artificial ageing of mineral oils reported by Besser et al. [15], was followed to oxidize the oil samples in the short term. For this, 300 g of oil were heated in a sealed beaker, comprising an air inlet and an exhaust gas vessel, at 160±5 °C for 60 h using a stirring hotplate. Air was introduced into the beaker at 10 L/h, as suggested in the method. The sample was agitated throughout the test to promote uniform oxidation, while oil temperature was monitored.

2.2. Oxidation, thermal stability and viscosity measurements

Oxidation was evaluated in terms of changes in carbonyl compounds produced in the oils by FT-IR analyses according to the standard method ASTM D-7214. The oxidation characteristics of the oil samples were evaluated by using the standard method ASTM D-7214. The method is based on measurements of the change in concentration of constituents containing a carbonyl function by Fourier transform infrared spectroscopy (FT-IR) in a spectrometer micro Raman (LabRam HR800) coupled to an ATR (objective 36X) from a module FT-IR (IR2). The FT-IR spectra of the fresh and aged oils in a transmission cell of known pathlength are recorded between 700 and 1900 cm^{-1}, averaging 32 scans with a resolution of 4 cm^{-1}. The spectra from the fresh and aged oil samples are converted to absorbance, and then, subtracted. A baseline is set under the peak representing the carbonyl region (from 1650 to 1820 cm^{-1}) from the differential spectrum. The area shaped by this baseline and the carbonyl region identified is calculated and divided by the cell pathlength (0.05 mm). The result obtained is reported as the peak area increase (PAI) that represents the quantification of change in carbonyl compounds.

Oxidation stability of Jatropha oil was determined in a Rotary Pressure Vessel Oxidation Test (RPVOT) apparatus according to the ASTM-D2272 standard procedure. A paraffinic base oil (Shell HVI 60) and a formulated oil (SAE 10W-30) were additionally tested for comparison. For the test, 50±0.5 g of oil was blended with 5 ml of distilled water. Then, the blend is heated up at 150±0.1°C. A sanded copper catalyst with weight of 55.6 ± 0.3 g is used in the test. Once the pressure vessel is assembled and purged, the pressure vessel is charged with 620 kPa. The test is considered as finished once the pressure drops by 175 kPa. So, the time recorded in minutes (RPVOT time) represents the oxidation stability of the oil sample. All samples were run twice, and the average time is reported.

The rheological changes in the oils due to thermo-oxidation were evaluated at 26, 40 and 100 °C, respectively, by measuring dynamic viscosities and densities using a rotational rheometer (AR-G2, TA Instruments) with a cone and plate configuration and a glass borosilicate pycnometer, respectively. In addition, the viscosity index was determined according to the ASTM D-2270 standard procedure.

2.3. Friction test

A pin-on-disk tester was adapted to measure friction coefficients of a commercial wet clutch from an 8-cylinder pick-up truck equipped with an automatic transmission. A schematic representation of the test set-up is illustrated in Fig. 1. The pins were 9 mm diameter circular samples sectioned from an actual cellulose fiber composite material friction disk. Each pin sample is fixed at the bottom of the pin holder as illustrated in Fig. 2a. The disk samples were actual low-carbon steel disk separators from the clutch as shown in Fig. 2b. An oil sample and a disk sample are placed into the disk holder-oil container. An actual wet clutch cage was adapted to serve as the disk holder-oil container. The friction material sample is loaded axially with a constant load while is full in contact with the steel disk surface. The motor of the tester has a controller to adjust a predefined rotational speed of the disk in the range of 10±2 and 400±2 RPM. The friction force is recorded via a load sensor and a data acquisition program, while temperature is monitored by a thermocouple located close to the friction interface and immersed in the oil. A hot air gun was used to increase and maintain oil temperature by heating up the disk holder-oil container constantly. The friction force was measured at fifteen sliding speeds for periods of 90 s for each speed using the same pair of specimens and oil sample. The trials started with a sliding speed of 0.05±0.01 m/s increasing to 0.9±0.01 m/s with intervals of 0.06±0.01 m/s, accumulating 634±1 m of sliding distance to obtain the behavior of friction coefficient *vs* sliding speed for each oil sample. The total sliding distance was selected based on the minimal degradation and damage of the steel disk and friction material surfaces exhibited under these conditions in pretesting. This helped in limiting the analysis of changes of friction coefficient due only to thermo-oxidation and not to significant surface damage. However, to have an insight in the surface damage caused by the experiments, both the friction material and steel disk surfaces were evaluated by optical profilometry to determine the changes in surface roughness caused by sliding. It was assessed via measurements of the roughness of area (Sa) on three random images over the surface for each specimen. In the friction tests, a load of 51 N was applied to the pin to produce an apparent contact pressure of 0.8 MPa, which is in the range of engagement contact pressures (0-2.9 MPa) for wet clutches from moving off-road vehicles´ automatic power shift transmissions [16]. The tests were run at 26±1 °C and 100±5 °C, and three similar tests for each lubricant and temperature were carried out. The pin and disk samples were replaced for new ones after each set of trials.

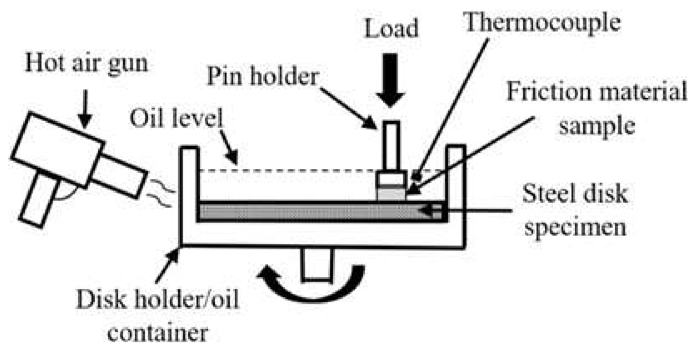


Figure 1. Schematic view of the pin on disk set-up.

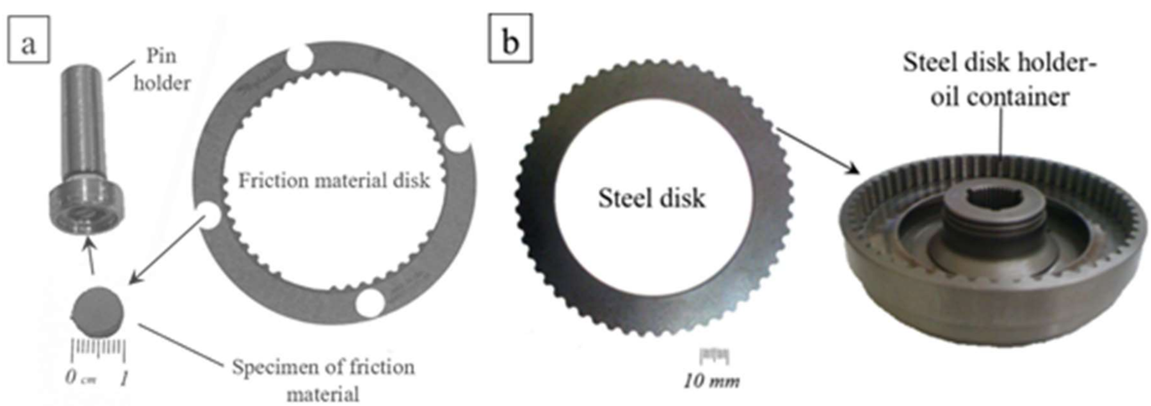


Figure 2. Specimens and holders used for the tests: a) pin specimens extracted from actual wet clutch´s friction plates; b) actual wet clutch´s steel plates used as disk specimens.

3. Results and discussion

3.1. Oxidation

The FT-IR spectra of the oils appear in Figs. 3a-c. Oxidation of mineral and synthetic based oils can be determined by a growth of the area between 1650 and 1820 cm^{-1}. This area, the carbonyl region, is characterized mainly by the increase of absorbance in peaks near to 1728 cm^{-1}. The spectra for the ATF appear in Fig. 3a, it shows an increase in the carbonyl region suggesting that it was oxidized to some extent. The peak localized close to 980 cm^{-1} corresponds to zinc dialkyldithiophosphate additives (ZDDPs) which are ubiquitous in ATF formulations, meanwhile the peaks near to 1377 and 1460 cm^{-1} correspond to the C-H bending modes of oil molecules [17]. The difference in those regions is minimal for the aged ATF, suggesting that ZDDPs and oil molecules were almost not affected by thermo-oxidation. The spectra obtained for Jatropha oil samples are shown in Fig. 3b. They were reported previously in [13] and are included here for purposes of comparison with those from ATF and B20-ATF. The main characteristic changes found were formation of saturated aldehyde functional groups or other secondary oxidation products and dimer carboxylic acid causing further polymerization and viscosity increase. The spectra shown in Fig. 3c correspond to those obtained for B20-ATF. A slight growth was found in peaks near to 1728, 1746, 1238, 1163, 1099, 990 and 970 cm^{-1} for aged B20-ATF. It correlates well with those characteristic peaks identified in the spectra from aged Jatropha oil [13]. So, the oxidation of B20-ATF may be ascribed mostly to oxidation of Jatropha oil´s compounds in the blend. The quantification of carbonyl compounds (peak area increase values) obtained for the oils is summarized in Fig. 4. It suggests that Jatropha oil was the most oxidized meanwhile B20-ATF exhibited a slightly higher oxidation than ATF after the thermo-oxidative process.

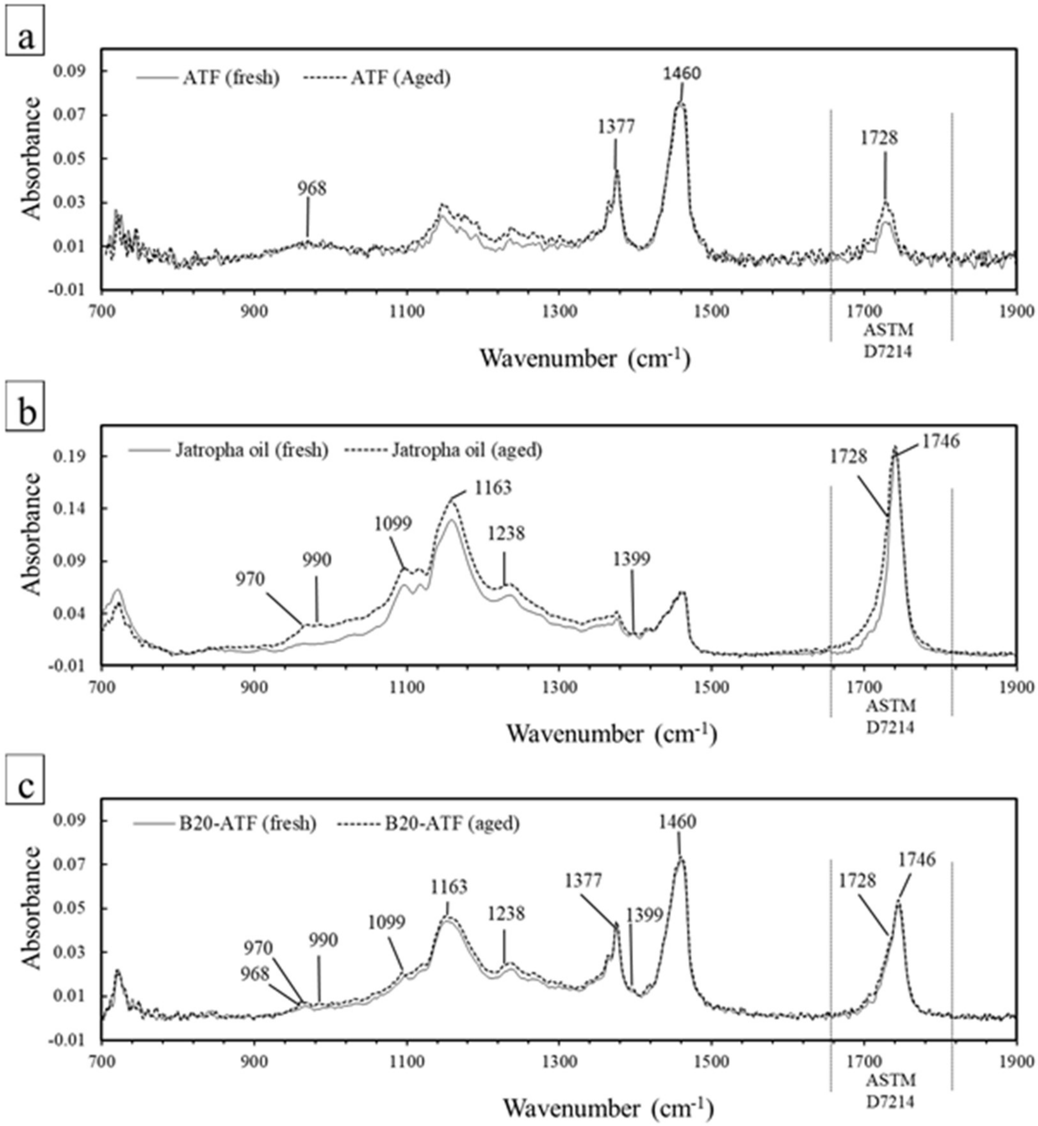


Figure 3. FT-IR spectra obtained for fresh and aged oils samples: a) ATF; b) Jatropha oil; c) B20-ATF.

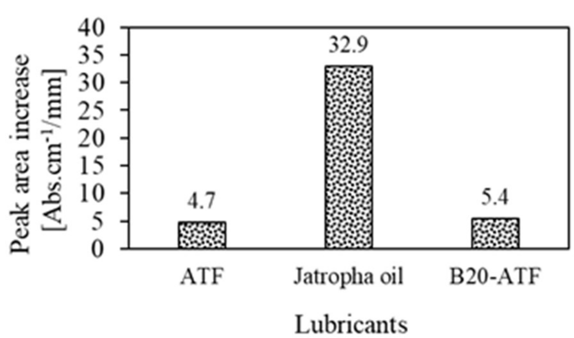


Figure 4. Peak area increase (PAI) values obtained for the oils.

3.2. Thermal stability

According to the conditions of the thermal stability method, the RPVOT times obtained represent a combination of both thermal and hydrolytic stability, since distilled water is added to the oil samples [18]. The RPVOT times obtained for the oils are displayed in Fig. 5. RPVOT time of 25 minutes was obtained for Jatropha oil, 32.5±2 minutes for mineral base oil and 522.5±3.5 minutes for the formulated oil. These results were somehow expected because of the nature origin of Jatropha oil. However, the RPVOT time for Jatropha is slightly higher than those for other vegetable oils, namely, Canola, Castor, Corn, Soybean, Cuphea, Lesquerella, Meadowfoam, pennycress and passion fruit, which exhibit RPVOT times from 7.5 to 20 minutes as reported in [19, 20]. It is important to recall at this point that the Jatropha oil used in this work was not refined or chemically modified and it had considerable percentage (26.6%) of linoleic acid (polyunsaturated) which may promoted an accelerated oxidation in the oil. Therefore, the oxidation stability may be significantly improved by developing certain refining processes or other chemical modification as reported for other vegetable oils with significant contents of unsaturated fatty acids [19]. Moreover, amine antioxidants could be also added in certain proportions to increase RPVOT times as reported in [20]. The improvement of oxidation stability of JO by following these routes is subject of ongoing research in our group.

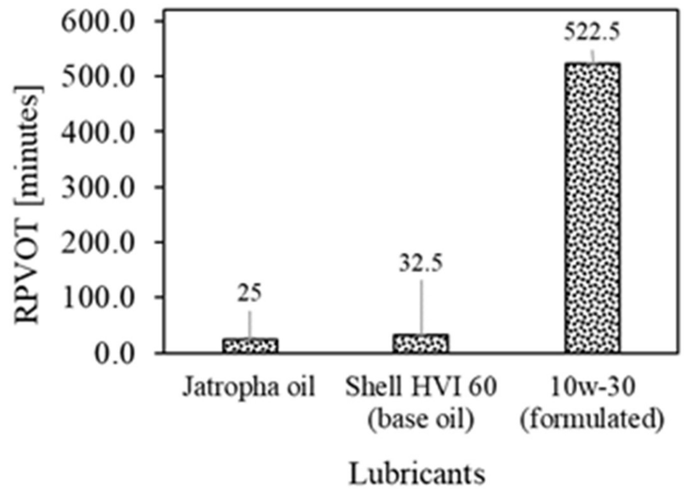


Figure 5. RPVOT times obtained for crude Jatropha oil, a base mineral oil (Shell HVI 60) and a formulated oil (10w-30).

3.3. Kinematic viscosity and viscosity index

The kinematic viscosities calculated are presented in Figs. 6a-b. Newtonian flow behavior of ATF, Jatropha oil and blends was not affected by thermo-oxidation, but shear viscosity of all oils was. Synthetic and mineral oils experience changes in viscosity due to dipole and van der Waals interactions and formation of hydrogen bonds caused by oxidized products and polar components, namely, carbonyl compounds, alcohols, benzene derivatives and esters [21]. Correspondingly, vegetable oils increase their viscosity due to enhanced intermolecular forces by formation of hydrogen bonds [22]. The kinematic viscosity of ATF increased slightly at 26°C and showed a small decrease at 100°C. The kinematic viscosity reduction at 100°C is ascribed to breaking of oil hydrocarbons by high temperature at an early oxidation stage and reduction of viscosity index [21]. B20-ATF and Jatropha oil showed a viscosity increase at both temperatures. However, Jatropha oil presented a much higher rise in viscosity due to rapid polymerization caused by oxidation. Although the increase in viscosity of B20-ATF was much lower than that of crude Jatropha oil, it was higher than the commercial ATF tested. This can be considered as negative for lubrication of automatic transmissions at some extent since ATFs operate also as hydraulic fluids. So, increased viscosity can generate power and friction losses by viscous shear in hydrodynamic lubrication elements and oil pumping. In Fig. 7, the viscosity indexes for the oils are displayed. It is well known that a high viscosity index is required for high-performance lubricants operating under variable temperature as ATFs. In general, vegetable oils exhibit higher viscosity index than mineral oils since they contain triglycerides which sustain intermolecular interactions when temperature raises [14]. According to the findings in this work, it was not the exception. Fresh Jatropha and ATF oils had the highest and lowest indexes, respectively. Viscosity index of ATF was enhanced by adding Jatropha oil only in fresh state, as evidenced in the B20-ATF viscosity index result. However, thermo-oxidation considerably reduced the viscosity index of Jatropha oil and B20-ATF in contrast to ATF, which presented a slight drop. Therefore, thermo-oxidation should be also considered in evaluating the rheological properties of bio-lubricants since it has a significant effect, not only on kinematic viscosity but on viscosity index as well.

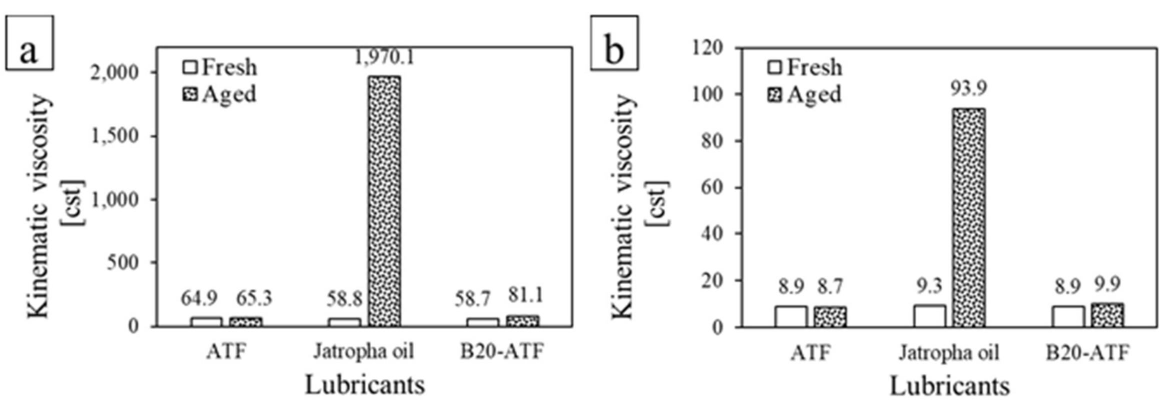


Figure 6. Kinematic viscosities obtained for the fresh and aged oils at: a) 26 °C; b) 100°C.

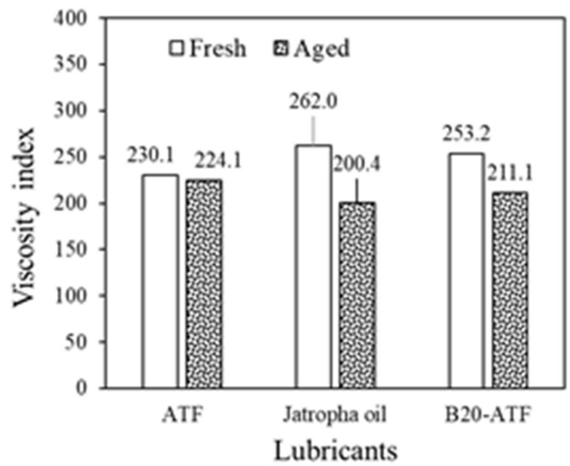


Figure 7. Viscosity index obtained for the fresh and aged oils.

3.4. Wet clutch friction

The lubrication regime of a lubricated contact can be determined by the knowing the Lambda (ʌ) ratio that can be calculated by the following expression [23]:

$$\Lambda = \frac{h}{\sqrt{{Rq_1}^2 + {Rq_2}^2}} \qquad (1)$$

where h is the minimum oil film thickness and Rq_1 and Rq_2 are the surface roughness from both surfaces. Hydrodynamic lubrication is expected for ʌ>3, mixed or partial lubrication when 1<ʌ<3, and boundary lubrication is generated for ʌ<1. The lubricating film, h, generated between the surfaces of a porous disk (friction material) and an impermeable material (steel disk) is influenced by different parameters that promote film thickness reduce with time. According to the sliding contact configuration in our experiments (see Fig. 8), the time required to decrease the lubricant film thickness to a defined value, h, at constant load can be approached by the model proposed by Prakash and Vij [24]:

$$\bar{t} = \frac{W {h_o}^2 t}{\mu A^2} = K \int_{\bar{h}}^{1} \frac{1}{\bar{h}^3(1+\xi)+12\varphi_o \bar{H}} \, d\bar{h} \qquad (2)$$

Where $\bar{t}$ is the dimensionless time, W is the load capacity, h_o is the initial oil film thickness, t is the time to decrease h_o to h, μ is the dynamic oil viscosity, A is the area of the porous material surface, K is a shape factor depending upon disc geometry, and ξ, φ_o and $\bar{H}$ may be determined by:

$$\xi = \frac{3s(2\alpha^2 s+\bar{h})}{\bar{h}(s+\bar{h})} \quad (3)$$

$$\varphi_o = \frac{\phi}{{h_o}^2} \quad (4)$$

$$\bar{H} = \frac{H}{h_o} \quad (5)$$

Where α is a dimensionless constant which depends on the characteristics of the porous material but is independent of the gap height and of the properties of the fluid [25], ϕ and H are the permeability and thickness of the porous material, respectively, and s may be calculated by:

$$s = \sqrt{\frac{\varphi_o}{\alpha}} \quad (5)$$

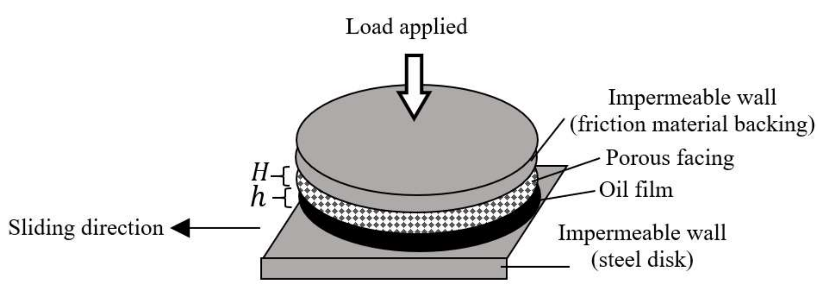


Figure 8. Squeeze film configuration for the pin-on-disk contact.

In order to determine the change of film thickness with time and the lubrication regime of the sliding contact of the experiments, the parameters given in Table 1 were used. The mean porous diameter, d, of the permeable material, which is the friction material in this case, is a required parameter to have an approximation of the slip coefficient, α. It was obtained by interpolating data reported by other authors [26], who correlated α with average porous diameter, as shown in Fig. 9, and using Eq. (6).

$$\alpha = 0.047e^{0.0036d} \qquad (6)$$

For determining the variation of the film thickness in the tribo pair aimed in this work, it was assumed that the sliding contact initiated with a full separation of the surfaces by the oil film (Λ=3) and it continued to decrease with time by effects of squeezing and porous diffusion transitioning to a mixed and a boundary lubrication regime.

Table 1. Parameters for estimating film thickness behavior under the squeeze film effect.

Parameter	**Value**	**Observations**	**Source of data**
ϕ [m^2]	7 x 10^{-13}	Data from a similar cellulose fiber composite material friction disk.	[27]
H [mm]	0.6	Thickness measured of the porous facing from the friction material samples tested.	-
K [dimensionless]	$\frac{3}{2\pi}$	Shape factor for a circular disk.	[24]
α [dimensionless]	0.048	Slip coefficient data obtained by interpolation considering the average porous diameter of the friction material (see Fig. 9).	[28]
d [µm]	10	Data from a similar cellulose fiber composite material friction disk.	[26]

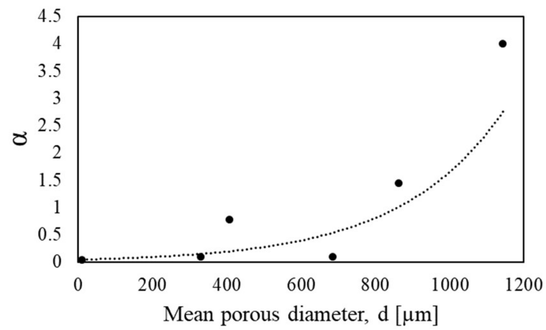
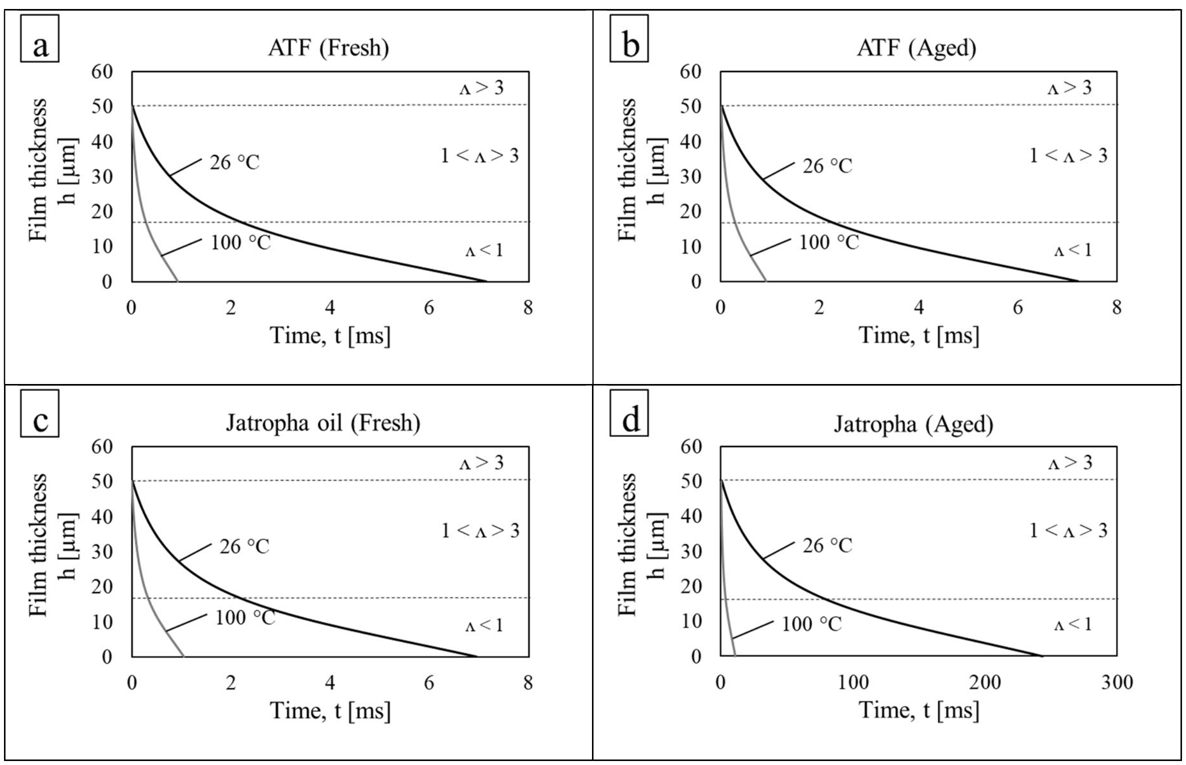


Figure 9. Correlation of slip coefficient with mean porous diameter.

In Figs. 10a-e, the behavior of the lubricant film thickness, h, with time is illustrated for all the oils and temperatures tested. It can be seen that the film thickness for the all the oils and temperatures has a substantial decrease with time. All the sliding contacts transitioned almost instantaneously (in less than 0.250 s) from hydrodynamic lubrication to boundary lubrication regime when the load was applied by the effect of squeezing before starting sliding. So, it was stated that all the tests were run under boundary lubrication regime since the beginning of the friction test.



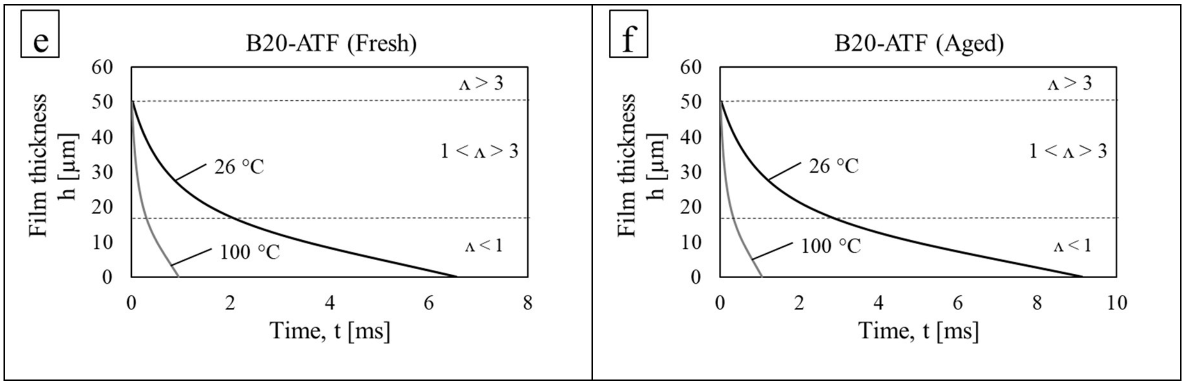


Figure 10. Calculated film thickness with time for the different fresh and aged oils tested at 26 and 100°C.

Figs. 11a-c show the comparisons of the mean friction coefficient with sliding speed obtained for the oils tested at 26 °C. ATF and B20-ATF presented an increase of friction coefficients for all speeds by thermo-oxidation. Nonetheless, those changes of B20-ATF were insignificant. The increased friction produced by thermo-oxidation of ATF can be considered as positive in some extent since higher friction in wet clutches is in general suggestable for allowing a higher torque transmission but lower friction values at the lowest sliding speeds (almost reaching the lock up stage) with tendency to increase with sliding speed, are suggestable for better anti-shudder performance (reducing vibrations during the wet clutch engagement) [29]. Both are properties required for wet clutch systems. Jatropha oil presented a considerable decrease of friction coefficient, mainly at low speeds after thermo-oxidation. This decrease can be associated to the huge rise in viscosity. Oil squeezing and porous diffusion at the sliding interface are phenomena occurring during the engagement and sliding of a wet clutch. They enable the torque transmission because the lubricating film is reduced. Much oil is squeezed and diffused into the friction material, and a great number of interactions of asperities take place transitioning from hydrodynamic to boundary lubrication regime almost instantaneously once the normal load is applied, and thus, producing higher friction and torque transferring. Hence, ATFs with low viscosity facilitate this process. In the case of aged Jatropha oil, the large viscosity at 26°C restricted, in large extent, oil squeezing and diffusion which perhaps generated larger lubricating film and produced very low friction coefficient values for all speeds. The comparisons of the mean friction coefficient with speed obtained for the oils at 100 °C are shown in Figs. 12 a-c. All tested oils presented different behavior than that exhibited at 26 °C. Friction coefficients of fresh ATF for all speeds were lower at 100 °C than those at 26 °C. This reduction of friction for ATFs with the rise of temperature have been already reported by other authors [29, 30]. It is related to the activation of additives, namely, friction modifiers at high temperatures promoting friction decrease. Thermo-oxidation also generated an increase of friction for ATF when tested at 100 °C. However, in contrast to the behavior observed at 26 °C, friction coefficients of aged ATF tended to decrease with speed at 100 °C, which may diminish anti-shudder property. Fresh Jatropha oil tested at 100°C presented the lowest friction coefficients for all speeds. However, thermo-oxidation raised friction coefficients, contrary to that occurring at 26 °C. This is because the viscosity of aged Jatropha oil at 100 °C was low enough to allow squeezing and porous diffusion rising friction. Friction coefficients of B20-ATF exhibited considerable changes by thermo-oxidation at 100 °C in comparison with those obtained at 26 °C. Fresh and aged B20-ATF presented a similar behavior (friction coefficients were increased by thermo-oxidation) than fresh and aged ATF, respectively, at 100 °C. Nevertheless, friction coefficients of B20-ATF were lower than those of ATF. Overall, the addition of 20%vol. Jatropha oil into the ATF (B20-ATF) helped in maintaining similar friction coefficients at 26 °C and a lower increase at 100 °C after thermo-oxidation in comparison to pure ATF.

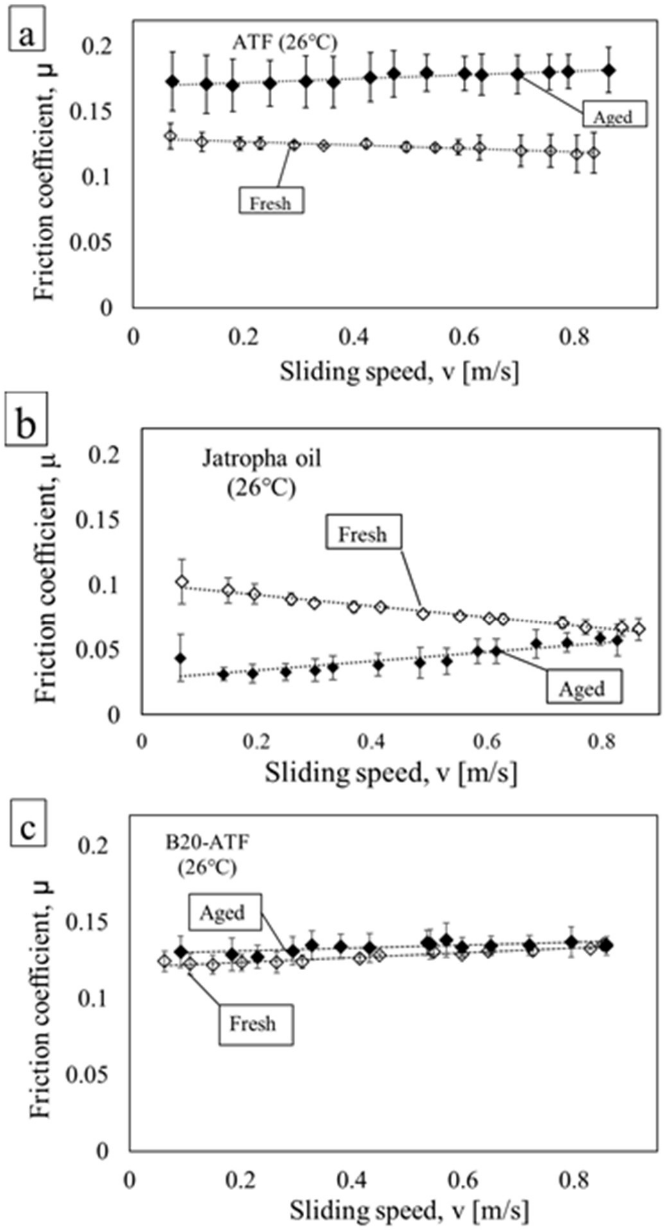


Figure 11. Comparison of friction coefficient vs sliding speed obtained at 26°C for the fresh and aged oils: a) ATF; b) Jatropha oil; c) B20-ATF.

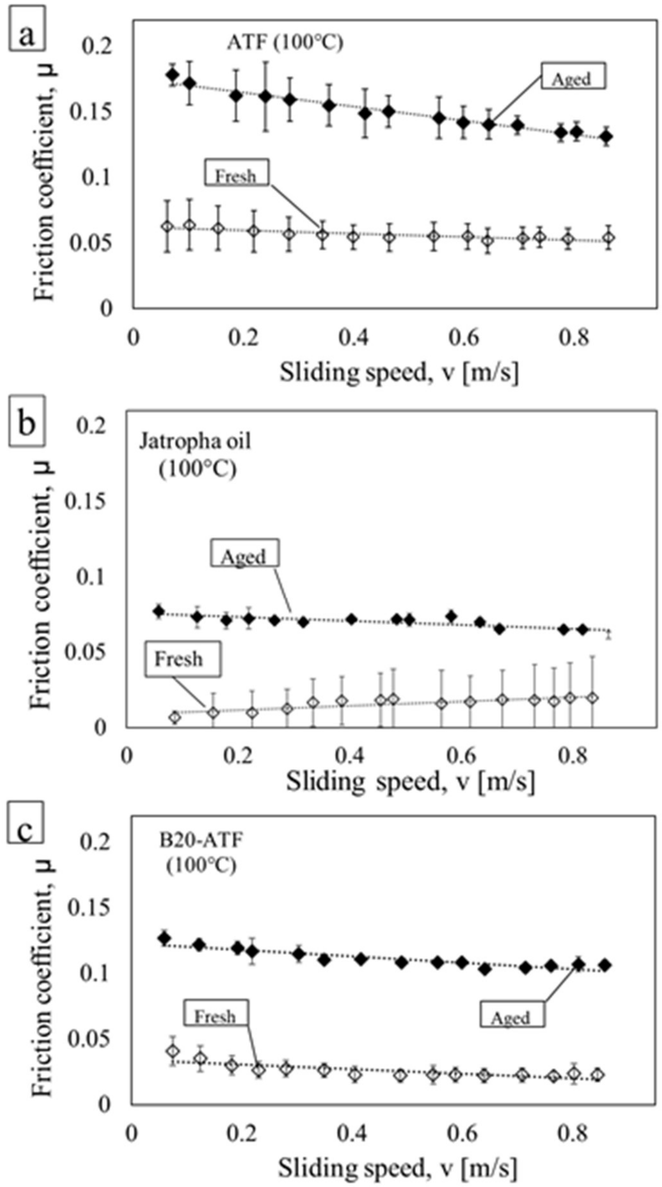


Figure 12. Comparison of friction coefficient vs sliding speed obtained at 100°C for the fresh and aged oils: a) ATF; b) Jatropha oil; c) B20-ATF.

In all the plots displayed in Figs. 11a-c and 12a-c, the friction coefficient increases or decreases along with the sliding speed. They were fitted by straight lines with slope dμ/dv. The dμ/dv values obtained from each mean curve are shown in Figs. 13a-b. These results are useful to have a first approach and visualization of the possible anti-shudder property of the oils [30]. Anti-shudder property is evaluated reliably by measuring the slope values, dμ/dv, under realistic operation by using full-scale testers (i.e. the SAE #II machine) since it depends on many other factors in the transmission hardware design, operation and assembly. However, the dμ/dv measurements in the pin-on-disk tester help to discard all those other factors by focusing only in the local friction produced in the wet clutch plates interface [31]. A good anti-shudder property is expected for positive dμ/dv values, while poor property is expected for negative dμ/dv values [8]. According to the present results, anti-shudder property of Jatropha oil and ATF could be improved by thermo-oxidation at 26°C, but worsened at 100°C. In the case of B20-ATF, thermo-oxidation did not produce significant anti-shudder property changes for both temperatures.

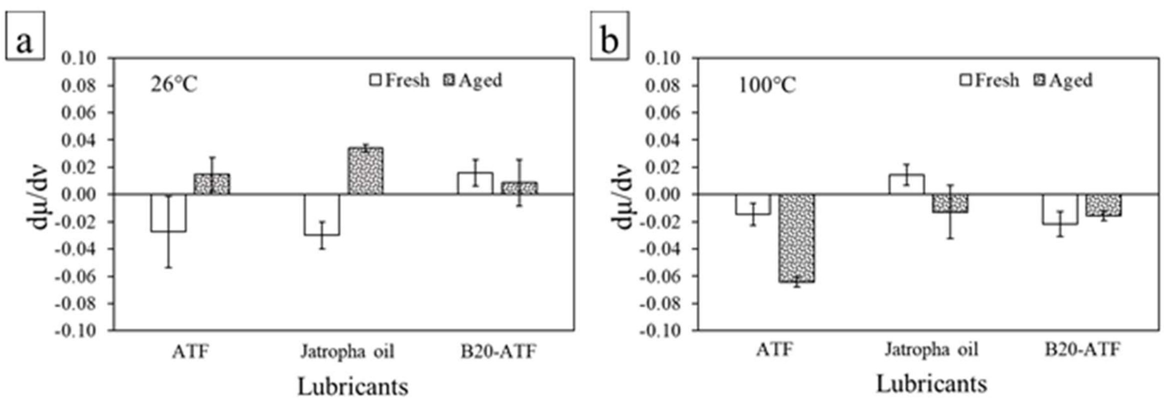


Figure 13. dμ/dv values estimated for the fresh and aged oils at: a) 26°C; b) 100°C.

The roughness changes occurred in the friction material and steel disk samples due to the friction testing can be seen in Figs. 14a-b and 15, respectively. For all the cases, the friction material samples and steel plates exhibited a reduction of surface roughness with very similar variation. The changes in surface roughness of the friction material samples are a representation that involves damage of the surface, plastic deformation of asperities and porosity changes occurred by sliding. On the other hand, considering the softness of the friction material and the low contact pressure (0.8 MPa) in the contact, the change of roughness of the steel disk surface is only related to wear caused which corresponds to polishing wear mechanism. Considering that there were not significant differences between the roughness variation occurred by using the different lubricants, the friction coefficient behavior changes (anti-shudder) can be ascribed majorly to the effects of thermo-oxidation and temperature of the oils. In order to look up more deeply into the effects of wear of the wet clutch materials on the anti-shudder behavior of the oils, much longer distances should be tested in future works.

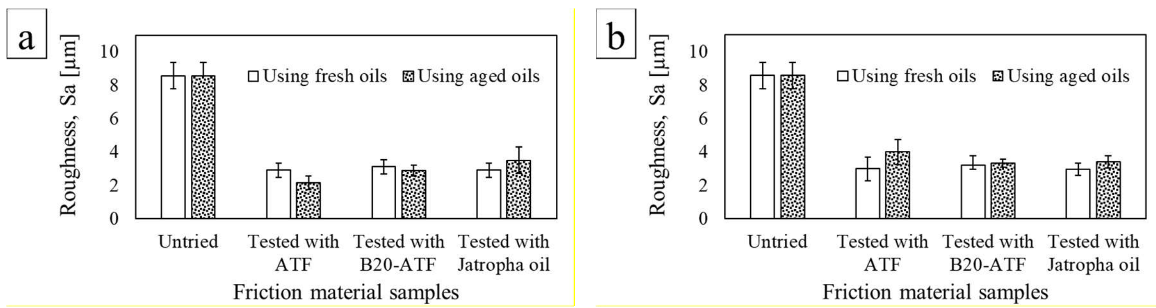


Figure 14. Comparison of surface roughness (Sa) changes from the friction material surfaces tested with the different oils at: a) 26 °C; b) 100°C.

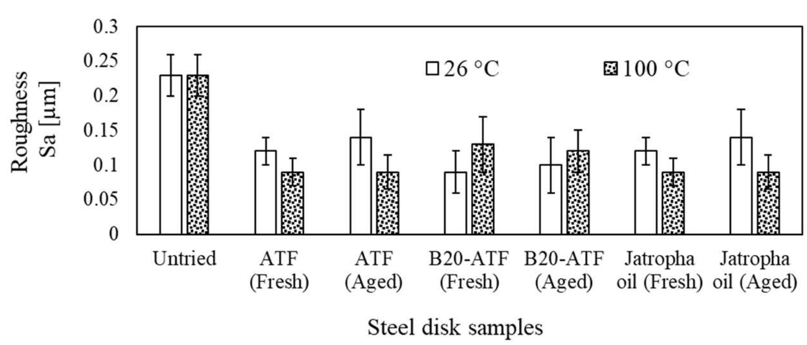


Figure 15. Comparison of surface roughness (Sa) measured from the surfaces of the steel disks tested with the different oils.

Finally, in comparison to ATF and B20-ATF, Jatropha oil was seriously oxidized and exhibited the highest increase in viscosity, the highest reduction of viscosity index, the largest variation (growth) in pressure-viscosity index, the lowest thermal stability and the lowest friction coefficients at both temperatures in the wet clutch due to thermo-oxidation. So, using pure Jatropha oil as an ATF would be unsuitable. Nonetheless, although B20-ATF was a bit more oxidized and presented a slightly higher increase in viscosity than ATF, the friction coefficients were lower for both temperatures and almost not altered at 26°C due to thermo-oxidation. Also, the viscosity index of fresh B20-ATF was greater than ATF in the fresh state. So, blending ATFs with Jatropha oil in low proportions (as an additive) could decrease friction coefficient of wet clutches reducing the magnitude of the possible torque transmission but improving the anti-shudder property, even under thermo-oxidative condition, and improve viscosity index in fresh state keeping tolerable viscosity changes by thermo-oxidation while contributing to environmental protection.

4. Conclusions

In this work, a study of Jatropha oil as a bio-ATF under thermo-oxidation was carried out by evaluating changes in kinematic viscosity, viscosity index, thermal stability and friction vs speed behavior of a wet clutch. The conclusions from this work can be drawn as follows:

- Jatropha oil was much more oxidized than ATF and B20-ATF by thermo-oxidation, while B20-ATF was slightly more oxidized than ATF. The PAI values (in Abs·cm^{-1}/mm) obtained were 32.9 for Jatropha oil, 5.4 for B20-ATF and 4.7 for ATF. The RPVOT time (oxidation stability) of Jatropha oil was 25 minutes, which is slightly higher than other vegetable oils.

- Newtonian flow of all oils was not modified by thermo-oxidation, but shear viscosity of all oils was. ATF exhibited a very slight viscosity changes at 26 and 100°C while Jatropha oil and B20-ATF presented a viscosity increase.
- In a fresh condition, Jatropha oil had the highest viscosity index of 262, meanwhile those of B20-ATF and ATF were 253.2 and 230.1, respectively. Thermo-oxidation considerably reduced the viscosity index of all oils; Jatropha oil and B20-ATF were the most reduced.
- Thermo-oxidation caused an increase in friction coefficients of ATF and B20-ATF for all speeds in the wet clutch at 26°C while it produced a considerable decrease for Jatropha oil at low speeds. Jatropha oil exhibited the lowest friction coefficients even after thermo-oxidation.
- At 100°C, all oils presented different behavior than that exhibited at 26°C. Friction coefficients of fresh ATF were lower at 100°C than those at 26°C for all speeds. Thermo-oxidation generated a rise of friction coefficients of Jatropha oil contrary to that occurring at 26°C. Friction coefficients of B20-ATF exhibited considerable changes by thermo-oxidation at 100°C in comparison with those obtained at 26°C. Fresh and aged B20-ATF presented a similar behavior than fresh and aged ATF at 100°C. Nevertheless, friction coefficients of B20-ATF were lower than those of ATF.
- Anti-shudder property of oils was analyzed by the dμ/dv values obtained from the pin-on-disk tests. Anti-shudder property of Jatropha oil and ATF was improved by thermo-oxidation at 26°C but worsened at 100°C. In the case of B20-ATF, thermo-oxidation did not produce significant anti-shudder property changes for both temperatures at the sliding distance tested.
- The friction material samples and steel plates exhibited a reduction of surface roughness with very similar variation. The changes in surface roughness of the friction material samples were related to plastic deformation of asperities and porosity changes occurred by sliding while the change of roughness of the steel disk surface was related to polishing.
- Finally, using pure Jatropha oil as an ATF would be unsuitable. However, blending ATFs with Jatropha oil in specific proportions may be suitable to decrease friction coefficient at low sliding

speeds, and thus improve anti-shudder behavior for wet clutches even under thermo-oxidative condition, while contributing to environmental protection.

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