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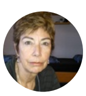

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Tallow Biodiesel: Properties Evaluation and Consumption Tests in a Diesel Engine

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Biodiesel is a biodegradable and alternative fuel to petroleum diesel. The methyl esters are produced from transesterification of vegetable oils or animal fats with alcohol in the presence of an acid or a basic catalyst. In this work, biodiesel was obtained by a transesterification reaction of bovine fat with methanol using KOH as a catalyst. The raw material and the biodiesel were characterized by their composition in fatty acids. Blends of diesel/biodiesel were produced in several concentrations and were assessed in relation to some combustible properties, according to the ASTM standards. The blends diesel/biodiesel and biodiesel (B100) were also compared with diesel through consumption tests in a diesel engine used for energy generation. All tests demonstrated that biodiesel and its formulations with diesel can present similar results, or sometimes better results, to those of mineral diesel.

1. Introduction

Historically, renewable energy resources have been mentioned as an important component in the research of a sustainable energy economy.[1,2]

For several decades, many studies have been performed looking for the use of an alternative fuel, which was economically viable and less pollutant than petroleum diesel. However, such research was sometimes not conclusive, until the present and growing environmental concern.[2–6]

Biodiesel is a renewable and biodegradable fuel that can be considered as an alternative to petroleum diesel.[4,6–9] It is produced from vegetable oils or animal fats, pure or residual, by catalytic transesterification with a simple alcohol (methanol or ethanol).[1,4,7,8,10–13] Many vegetable oils (rapeseed, corn, sunflower, soybean, or cotton) have been largely used in the production of biodiesel; however, much research has demonstrated that these pure oils are not adequate to substitute for diesel due to their high viscosity and molecular weight. These properties provide poor atomization, low volatility, incomplete combustion, and solid residues in the engine.[2,5,12–14] For this reason, the oil must be transformed into esters before use as fuel. Then, the mixture of alkyl esters of fatty acids from vegetable oils or animal fats is named biodiesel and used in diesel engines, pure or blended with mineral diesel.

Conventional diesel is formed by distinct hydrocarbon chains (14−18 carbons per molecule). It is composed of aromatic hydrocarbons (benzene, toluene, xylenes, and other hydrocarbons), sulfur, and other residues from the crude oil. However, biodiesel has a different composition, and the alkyl esters of fatty acids are composed of chains with 14−20 carbon atoms with two oxygen atoms at the end of the chain.[14] Approximately 10% of the weight of biodiesel is due to oxygen; it does not contain sulfur, aromatic compounds, metals, or crude oil residues.[5,14–17] This fuel also shows some important characteristics such as higher cetane number and lower flash point if compared with conventional diesel.

The market for biodiesel is associated with agricultural or cattle activities, and its price is slightly superior to diesel.[16–18] But, if the byproducts (glycerin, catalyst, and residual alcohol)

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are adequately recovered in the process, its production can be competitive with commercial use of fossil fuels.[4,19]

The use of alkyl esters as fuel seems to be promising because their fuel properties are similar to those of diesel, allowing their use without expressive changes in the engines.[2,6,10,16,20] Besides this, some properties of biodiesel can enhance the efficiency of combustion and the profile of emissions.[2,4,6,15,21,22] However, the reduction of the emissions (due to the use of an oxygenated fuel) depends on the molecular structure and the amount of biodiesel used.[6,20] The composition of diesel and the mixtures of diesel/biodiesel affect some properties such as density, viscosity, and volatility, mainly at lower temperatures.[20]

Animal fats (tallow or chicken oil) have similar properties to those of diesel, except for their high viscosity (highly dependent on the content of saturated compounds such as palmitic and stearic esters) that can cause problems in the ignition system.[15,18,23] The major advantage of the use of these materials is the low cost and the inexistence of byproducts such as the vegetable cake.

The animal fats differ from some vegetable oils, such as soybean or colza oil, with respect to their chemical properties. The composition of these oils presents a large amount of unsaturated fatty acids; however, in animal fats such as beef tallow, there are a large amount of saturated fatty acids.[8,22] The presence of this high concentration of saturated fatty acids influences two important properties of the fuels that are inverse: the oxidative stability (OS) and the cold filter plugging point (CFPP).[5,21–24] Both properties increase with the increase in saturated compounds in biodiesel, but higher OS is interesting because it implies higher stability while a larger CFPP is undesirable because the biodiesel tends to solidify during the winter, leading to a bad performance of the engine as a consequence.[5,22]

The mixture of alkyl esters of fatty acids of animal fat with the conventional diesel can be quite profitable for the industry of petroleum regarding the new demands seeking the decrease of the emissions of sulfur compounds, aromatics, and particulate material produced by the diesel engines.[21,25] In comparison with petroleum diesel, the use of fat biodiesel can reduce the level of noise in a diesel engine and the environmental pollution.

The goal of this study was to characterize the raw material and their alkyl esters and to compare some properties of this biofuel, produced from cattle fat, with petroleum diesel. In addition, this study also seeks to evaluate the engine consumption with biodiesel and its blends with petrodiesel.

2. Experimental Section

2.1. Materials and Methods. The beef tallow, used in the biodiesel production, was acquired in some slaughterhouses in the area of Pelotas city (RS/Brazil). The methanol and the potassium hydroxide, used in the transesterification process, were of commercial grade and acquired in the local market. The biodiesel used was produced by alkaline transesterification in a biodiesel pilot plant located in the south of Brazil (installed in the Federal University of Pelotas (UFPel)), and the metropolitan diesel was purchased in the local market.[26]

2.2. Biodiesel Production. The production of biodiesel from beef tallow was accomplished by the transesterification of the bovine fat (800 kg) with methanol (200 L) in the presence of potassium hydroxide (16 kg), which is a strong basic catalyst. The reaction was developed in a tubular reactor with a production capacity of 800 L per day at a temperature of 65 °C. The reaction time for the conversion of the esters was 90 min. The glycerol formed as a byproduct of the reaction was separated from the methyl esters by using two washing steps.

2.3. Conversion and Characterization of the Fatty Acid Methyl Esters (FAMEs). The quantitative determination of the total esters in biodiesel was made by gas chromatography with a flame ionization detector (GC/FID, Shimadzu GC 17A), equipped with a Carbowax-20 M open tubular column (30 m × 0.25 mm × 0.25 m). The temperature program was from 160 to 200 °C at 20 °C/min and from 200 to 230 °C at 5 °C/min with a 6 min hold. The detector and injector were maintained at 220 °C; helium was used as the carrier gas with a flow rate of 1.0 mL/min, and the split rate was 1:50. Methyl dodecanoate was chosen as the internal standard for the internal standard quantitative calculation.

The total of residual methanol was determined also by GC/FID with an OV-5 capillary column (30 m × 0.25 mm × 0.25 m). The temperature program was from 50 to 100 °C at 2 °C/min. The other conditions were the same as those used for the esters determination. The internal standard used in this case was isopropyl alcohol.

The qualitative analysis of raw material and biodiesel was made by gas chromatography with mass spectrometry (GC/MS) in a Shimadzu QP 5050A instrument with a OV-5 capillary column (30 m × 0.25 mm × 0.25 m). The transfer line and injector were maintained at 280 °C. Helium was the carrier gas with a flow rate of 1 mL/min, and it used a split injection at a 1:50 ratio. The FAME composition was determined by comparing the mass spectra of each peak with those from the library of GC/MS and also by additional comparison of the GC retention times of the chromatographic standards. The tallow was first derivatized with methanol/BF_3 prior to gas chromatographic analysis. The GC analysis of triglycerides in fats and oils is normally made after their conversion into the corresponding fatty acid methyl ester derivatives (FAMEs), due to their low volatility. Methanolysis with boron trifluoride (BF_3) followed by solvent extraction is a well-established procedure for profiling fatty acids in oils and fats. Beef tallow (raw material) was analyzed following the AOAC-IUPAC official method with slight modifications.[27–31] About 150 mg of oil was refluxed for 10 min with 4 mL of methanolic NaOH (0.5 M). Then, 5 mL of methanolic BF_3 was added, and the mixture was refluxed for 2 min, followed by the addition of 10 mL of *n*-hexane. After cooling, a saturated NaCl aqueous solution was added under stirring, and then the hexane layer containing the FAMEs was separated, dried over anhydrous sodium sulfate, and diluted prior to GC/MS analysis.

2.4. Preparation of the Mixtures of Diesel/Biodiesel. The mixtures of fuels were obtained by a volumetric blend of biodiesel of bovine fat with metropolitan diesel. Seven formulations were used (B2, B5, B10, B20, B30, B40, and B50) in which the number accounts for the percentage of blended biodiesel in volume. The mixtures were prepared at 60 °C under mechanical mixing.

2.5. Physical and Chemical Properties of the FAMEs. Some properties of the fuels, such as density, viscosity, flash point, and

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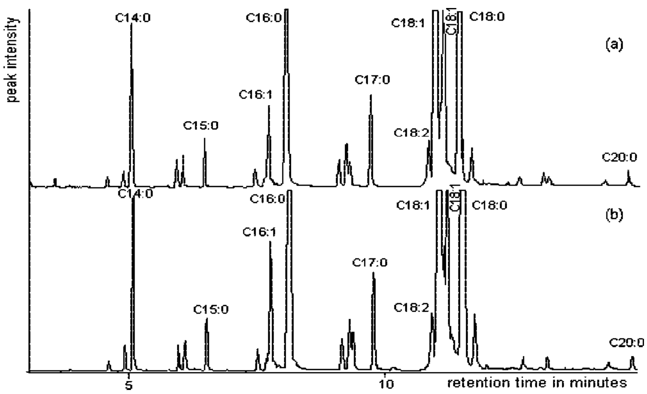

Figure 1. Chromatograms (GC/MS): (a) beef tallow; (b) biodiesel.

pour point, were assessed in agreement with the specifications of the Associação Brasileira de Normas Técnicas (Brazilian Association of Technical Norms) (ABNT) and the American Standards Techniques and Methods (ASTM). The distillation range was accomplished according to the method specified in NBR 9619 of the ABNT and D 86 of the ASTM in the laboratory of fuels of the Federal Center of Technological Education of Rio Grande do Sul. The determination of iodine value, acid number, soap index, potassium amount, and sodium amount was accomplished at the laboratories of analytical chemistry of the Federal University of Rio Grande do Sul (UFRGS) in agreement with the ASTM and the American Oil Chemists (AOC).

2.6. Engine Tests. The efficiency of the combustion process was evaluated through the specific consumption [g/(kW h)] by using a Toyama air cooled engine diesel generator with a nominal power of 4000 W. The engine operated at 3600 rpm with the fuel injection pump self-adjusted to deliver 240 V to the electric generator. The energy produced in the generator feeds the bank of 1800 W electrical resistors. The power delivered to the generator is the product of the voltage and the amperage, whose data was collected through the CIO-DAS 08 (Measurement Computing Corp.) data acquisition board. The fuel flow was calculated from the tangent of the plot obtained by measuring fuel mass as a function of time. The specific fuel consumption was calculated as the flow rate divided by the power. The engine operated with diesel/biodiesel mixtures. Fuel consumption measurements of 10 min were first carried out with petrodiesel, used as reference fuel, and then repeated for each of the diesel/biodiesel blends.

3. Results and Discussion

3.1. Chromatography Characterization of the Raw Material and Biodiesel. Figure 1 shows the gas chromatogram (GC/MS) for tallow (after derivatization with methanol/BF_3) and for the biodiesel obtained from it. Table 1 displays the composition of the raw material and biodiesel, showing that the composition of both is very similar. The last column in this table shows the normal composition of soybean oil,[32–36] which indicates that the main differences appear in the amount of saturated methyl esters in tallow while soybean shows low concentrations of this compound. The ratio saturated/unsaturated of both soybean and tallow is also different. The fact that the FAMEs from tallow present a great amount of saturated fatty acids is advantageous because the saturated compounds (C14:0, myristic; C16:0, palmitic; and C18:0, stearic) have high cetane numbers and they have less propensity to oxidize and polymerize than the unsaturated ones. However, the saturated fatty acids present a tendency to crystallize at low temperatures, which can limit the use of this fuel in areas of a cold climate.[4,5,37,38]

3.2. Physical and Chemical Properties of the Methyl Esters of Animal Origin. Table 2 shows some of the physical and chemical properties of biodiesel and bovine fat.

Iodine Number. The iodine value is directly related to the degree of unsaturation in the fatty acid molecule; in other words, the iodine number increases as the number of double bonds in the compound increases.[9,37] This property has importance because it is a direct indication of the oxidative stability (OS) of the fuel.[9]

The OS of fatty acid methyl esters (biodiesel) is defined as a measure of their degree of resistance to oxidation, which depends on the unsaturation degree and the position of the double bond along the molecules, and it could cause the formation of deposits in the motor and the deterioration of the lubrication oil. This problem affects biodiesel mainly during storage.[1,9,37] The autoxidation of the fatty esters is one of the major inconveniences that can affect the use of biodiesel.

The allylic position of double bonds is especially susceptible for the oxidation. The literature presents relative averages of oxidation that are 1, 41, and 98 for oleic esters (methyl or ethyl), linoleic, and linolenic, respectively.[1,9,11] These data are of fundamental importance, taking into account that most of the biodiesels contain significant amounts of unsaturated FAMEs.[9]

Table 2 clearly indicates that the biodiesel used in this work as well as the raw material presents low values of iodine index if they are compared to esters from unsaturated fats; this is coherent with the idea that the bovine fat shows a larger concentration of saturated fatty acids, favoring its OS and allowing large storage time without chemical deterioration.

Acid Number. The test of acidity, similar to that of viscosity, is a simple method to monitor the quality of the fuels.[11] The acid number (AN) should be one of the first assessing analyses, since this value can reflect the efficiency of the process of obtaining biodiesel. If the AN is high (superior to 2 mg of KOH per gram of sample), it is possible to assume that some free fatty acids (FFA) remain in the biodiesel. Also, the acid wash applied after the transesterification to remove the alkaline catalyst avoiding soap formation can be responsible for high acid numbers. An increase in the AN can cause deposits in the motor[37,39] and corrosion problems.

The two samples (fat and biodiesel) presented similar AN values and were in agreement with the limits specified by the norm that the maximum is 0.8 mg KOH/g of sample.

Sodium, Potassium, and Soaps. The contamination with potassium or sodium is originated by the use of catalysts in the process of production of biodiesel in the form of KOH or NaOH; however, both ions can cause the formation of insoluble soaps that generate deposits in the motor and also catalyze polymerization reactions.

At the end of the transesterification reaction, the catalyst excess and the soaps usually stay in the glycerin phase; however, some soap and a small amount of residual catalyst can remain in the methyl ester phase. For this reason, during the process of obtaining biodiesel, it can be advantageous to evaluate the

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Table 1. Qualitative and Quantitative Compositions of the FAMEs of Beef Tallow, Biodiesel, and Soybean Oil

peak	t_R	no. C	acid[a]	formula	tallow	biodiesel	soybean oil
1	5.05	C14:0	myristic	$C_{13}H_{26}O_2$	2.68	2.76	0.1
2	6.50	C15:0	pentadecanoic	$C_{15}H_{30}O_2$	0.93	0.79	nd[b]
3	7.76	C16:1	palmitoleic	$C_{17}H_{32}O_2$	1.90	2.14	0.1
4	8.13	C16:0	palmitic	$C_{17}H_{34}O_2$	26.18	24.47	10.6−13.2
5	9.79	C17:0	heptadecanoic	$C_{19}H_{32}O_2$	1.74	1.59	nd[b]
6	10.12	C18:3	linolenic	$C_{19}H_{32}O_2$	nd[b]	nd[b]	1.8−7.6
7	10.93	C18:2	linoleic	$C_{19}H_{34}O_2$	0.76	0.74	51.5−56.2
8	11.07	C18:1	oleic (cis isomer)	$C_{19}H_{36}O_2$	30.09	29.66	22.9−24.4 (cis + trans)
9	11.15	C18:1	elaidic (trans isomer)	$C_{19}H_{36}O_2$	1.74	1.90	
10	11.54	C18:0	stearic	$C_{19}H_{38}O_2$	33.69	35.70	3.9−4.2
11	14.88	C20:0	arachidic	$C_{21}H_{42}O_2$	0.30	0.25	0.3
12	16.92	C22:0	behenic	$C_{23}H_{46}O_2$	nd[b]	nd[b]	0.3
			total of saturated		65.52	65.56	11.3−13.9
			total of unsaturated		34.48	34.44	80.2−92.5

[a] Methyl esters. [b] nd = not detected.

Table 2. Values of Acid and Iodine Number, Amounts of Sodium and Potassium, and Soap Index of Biodiesel and of the Beef Tallow

sample	esters (%)	methanol (%)	acid no. (mg of KOH/g of sample)	iodine index (g of I_2/100 g)	Na (mg kg^{-1})	K (mg kg^{-1})	soap (ppm)
tallow			0.69	44.65			
tallow biodiesel	95.0	0.06	0.70	41.52	1.63 ± 0.52	<0.50	76.06

Table 3. Comparison of Some Fuel Properties of Metropolitan Diesel (D) with Biodiesel (B100) and with Biodiesel/Diesel Blends

property	method	ASTMD6751 limit (B100)	limit (D and B2)[a]	diesel	B2	B5	B10	B20	B30	B40	B50	B100
density (20 °C kg/m^3)	ABNT NBR 14065		820−865	843.7	844.4	845.0	846.4	849.1	851.7	854.7	857.3	871.8
flash point (min, °C)	ABNT NBR 14598	130	min 38.0	40.7	43.0	43.7	44.0	46.7	48.3	52.3	56.7	156.7
kinematic viscosity (40 °C, mm^2/s)	ABNT NBR 10441	1.9−6.0	2.0−5.0	2.7	2.7	2.8	2.9	3.1	3.3	3.5	3.7	5.3
CFPP (max., °C)	ASTM D 6371			−15.3	−11.7	−8.3	−4.3	−3.0	−1.8	2.0	3.3	14.3
distillation curve (°C)	ASTM D 86											
initial temp				137.6	135.7	133.4	136.8	136.9	140.9	142.4	145.1	307.1
50%				267.0	270.7	273.8	278.5	293.1	306.0	313.0	320.5	331.0
90%		360 max	360 max	372.1	373.8	370.2	357.8	361.6	358.6	354.4	349.7	343.0
final temp				400.1	400.9	399.4	386.1	383.4	376.0	370.2	363.6	344.4

[a] The limits in Brazilian legislation for petrodiesel (D) and for 2% of biodiesel in a biodiesel/diesel blend.

amount of formed soap and the efficiency of the wash process for the removal of these compounds. The amount of potassium and sodium according to Table 2 remained below the limit for the Brazilian rules for biodiesel (10 mg kg^{-1} in the ANP 42 standard regulation). The amount of soaps, for which was also found a small value (76.06 ppm), belongs to the total contamination item, which does not have a stipulated limit by the resolution ANP 42.

Then, from the results found in the three tests, it was possible to observe that the washing process used in the production of biodiesel was efficient and did not leave an amount of residual catalyst and soaps considered significant for affecting the quality of the final biofuel.

3.3. Fuel Properties of Biodiesel and Biodiesel/Diesel Blends. Table 3 shows the main fuel properties of biodiesel and biodiesel/diesel blends. In this table are also shown the limits for Brazilian legislation and also for American specification (ASTM 6751).

Density. The measure of the density has the objective of restricting the use of some materials as raw material for biodiesel production.[11] The density and other characteristics such as volatility and viscosity are usually independent, and they exert a great influence in processes such as the injection of fuel and its preparation for the automatic ignition. Consequently, acceptable parameters should be obtained for each physicochemical property with the objective of optimizing the combustion process of the engine.[20] Although the norms of the ABNT specify limits of density just for diesel and for the diesel/biodiesel blend (B2), the tests accomplished in this work also evaluated the density of other formulations (Table 3), which showed that only B100 presented density values above the limit stipulated for the metropolitan diesel used as a reference. The formulations resulted in density values similar to those of the diesel, varying from 844.4 to 857.3 kg m^{-3}.

The literature reports that mineral diesel and biodiesel have very similar densities; however, it should be taken into account that the density of biodiesel varies as a function of the raw material used in its production.[1] The reason for establishing a minimum value for the density is due to the need for obtaining a maximum engine power through the fuel flow control in the injection pump. In addition, this specified value prevents the formation of smoke when it operates with maximum power.

Kinematic Viscosity. With the advent of low-sulfur petrodiesel, the issue of fuel lubricity has become increasingly important as hydrodesulfurization removes polar compounds responsible for the lubricity of petrodiesel. Biodiesel added at low blend levels (1–2%) can restore the lubricity to low-sulfur petrodiesel,[40] since the low viscosity of biodiesel is an important but not sufficient property for imparting lubricity.

The reduction in viscosity is the major reason why alkyl esters of oils are used as fuel and not the crude oil.[11] The viscosity of biodiesel is slightly greater than that of petrodiesel but approximately an order of magnitude less than that of the parent vegetable oil or fat.[41] Biodiesel and its blends with petrodiesel exhibit temperature-dependent viscosity behavior similar to that

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(41) Gros, A. T.; Feuge, R. O. *J. Am. Oil Chem. Soc.* **1952**, *29* (8), 313–7.

of neat petrodiesel.[42] However, kinematic viscosity (at 40 °C) is the parameter required by biodiesel and petrodiesel standards.

The kinematic viscosity is used in the monitoring of the quality of biodiesel during storage, because it increases continuously with the decrease of the quality of the fuel.[11,13] The viscosity is the measure of the resistance to the "flowing off" of the fuel.[20] This physical property can also be used to select the profile of fatty acids in the raw material used for the production of the biofuel. An increase in the length of the chain and/or in the saturation degree proportionally increases the viscosity.[9,23] Factors such as the position and the configuration of the double bonds (a cis double bound presents a smaller viscosity than a trans one) can also have an influence on the viscosity.[9,24]

Biodiesel and its respective blends with conventional diesel usually present a viscosity that is a little higher than that of the pure conventional diesel, but it decreases with the increase in temperature.[43] A factor that can contribute to the increase in the viscosity of biodiesel is a contamination with glycerin.[1]

The methyl esters of bovine fat, as mentioned previously, present in its composition a high content of saturated fatty acids; therefore, the viscosity measured for pure biodiesel (5.3 mm^2 s^{-1}) was higher than the viscosity limit specified for petroleum diesel. However, as it can be observed from Table 3, all of the formulations of diesel/biodiesel presented values of viscosity inside of the limits stipulated for the conventional diesel.

The control of the viscosity has the objective to allow the good atomization of the oil and to preserve its lubricating characteristics. High viscosity values can bring other problems such as wear and tear of the lubricated parts of the injection system, leaking of the fuel pump, incorrect atomization in the combustion chamber, and damage to the pistons.[9,18,20]

Flash Point. The volatility of the fuels is expressed through distillation curves, flash point, and vapor pressure.[20] The flash point is the smallest temperature at which when the fuel is heated, under controlled conditions, it generates enough steam to form with air a mixture capable of inflaming.[1]

This property does not have influence in the operation of the motors; however, it is related to the inflammability, and it serves as indication of the precautions that must be taken during handling, transport, and storage of the fuel.[20] With regard to biodiesel, the specification of the flash point has the objective to limit the amount of alcohol in this biofuel. In agreement with the ANP, the minimum limit for the flash point is 38 °C. However, conventional diesel presents a flash point that usually varies from 54 to 71 °C while biodiesel presents a flash point above 93 °C. Consequently, biodiesel is considered a much safer fuel than diesel, with regard to stockpiling and fire risk.[1]

From Table 3, it is possible to observe that the pure biodiesel of bovine fat and its blends with diesel presented similar values of flash point that are higher than those of conventional diesel, used as a reference. All the values of flash points were above 38 °C, which confirms that the use of biodiesel involves a considerably lower inflaming risk than petroleum diesel.

Cold Filter Plugging Point (CFPP). One of the major problems associated with the use of biodiesel is its poor flow properties at low temperatures, indicated by a relatively high cloud point (CP) and pour point (PP). The CP, which usually occurs at a higher temperature than the PP, is the temperature at which a liquid fatty material becomes cloudy due to formation of crystals and solidification of saturates. The PP can be defined as the lowest temperature at which the substance will still flow. Saturated fatty compounds have significantly higher melting points than unsaturated fatty compounds; therefore, in a mixture, they crystallize at a higher temperature than the unsaturates do. Thus, biodiesel fuels derived from fats or oils with significant amounts of saturated fatty compounds will have higher CPs and PPs.[9,37] Both the CP and the PP can be estimated by the CFPP used mainly outside of North America (European standard EN 116).

Specifications related to low-temperature properties are included in biodiesel standards. The CP is the related property in ASTM D6751, but a limit is not given; rather, a report is required. This is due to the strongly varying weather conditions in Brazil.

The CFPP is discussed in EN 14214. Each country can select one of two options (moderate or arctic climate) for seasonal classes (summer and winter) and modify this specification based on national meteorological data.

The cold flow properties are considered the most important analysis of a fuel when it works in low temperatures because it influences the operation of the fuel directly in the motor at lower temperatures.

A parameter of the CFPP to low temperatures is not mentioned in the list of biodiesel specifications. Each country can use specific values for certain limits of temperature in different times of the year depending on the climatic conditions.[11]

The mixtures from B2 to B30 of bovine diesel/biodiesel presented negative results of the PP that were similar to those of conventional diesel. However, B100 and the formulations B40 and B50 presented PPs from 2 to 14.3 °C. This evaluation demonstrated that the blends from B40 to B100 must not be used for fueling engines in places where the temperature is relatively low, while the formulations from B2 to B30 can be used as fuel substitutes to mineral diesel without causing damage to engines in all the geographical areas that do not experience extremely low temperatures.

Distillation Range. Distillation tests for biodiesel, diesel/biodiesel blends, and reference mineral diesel were carried out while increasing the fuel temperature. The whole diesel volume distilled gradually, beginning at 137.6 °C and finishing at 400.1 °C, approximately. The diesel/biodiesel blends presented an initial temperature of distillation similar to that of diesel, varying between 133.4 and 145.1 °C. However, the pure biodiesel (B100) started to distill at a temperature of approximately 307.1 °C, and its distillation increased at a lower rate than that observed for mineral diesel. This happens possibly due to the fact that biodiesel is formed by compounds with very similar ebullition points.

The distillation curve exerts a direct influence in the evolution of the combustion. In the case of diesel, the characteristics of flash point and steam pressure vary as a function of the amount of light hydrocarbons, which are directly related to the initial point of distillation of the products. A decrease in the initial point of ebullition and in the temperature of the first fraction of the liquid recovered in the distillation indicates an increase in the volatility of the fuel that can be confirmed by the increase of the steam pressure and consequently the decrease in the flash point.[20] As mentioned previously, the FAMEs have very similar points of ebullition; consequently, biodiesel does not present a distillation curve. In the case of mineral diesel, the distillation curve is associated with properties such as viscosity, steam

(42) Tat, M. E.; Van Gerpen, J. H. *J. Am. Oil Chem. Soc.* **1999**, *76* (12), 1511–3.
(43) Joshi, R. M.; Pegg, M. J. *Fuel* **2007**, *86*, 143–151.

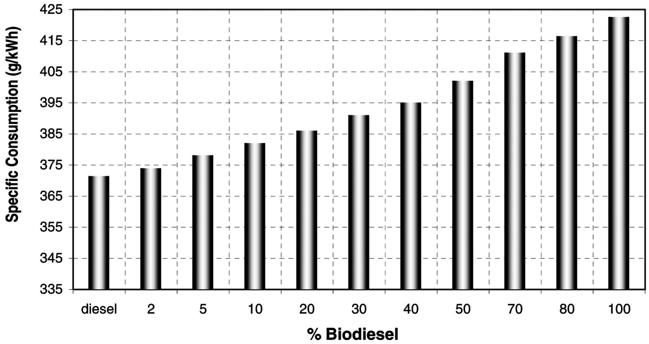

Figure 2. Comparison of the normalized specific consumption of diesel, biodiesel, and formulations of diesel/biodiesel in a Toyama motor monocylinder.

pressure, and average molecular weight.[11] Pure biodiesel presents approximate ebullition temperature limits at 327 and 346 °C.

3.4. Engine Tests. Figure 2 shows the results of the specific consumption [g/(kW h)] of diesel, biodiesel, and formulations of diesel/biodiesel (B2, B5, B10, B20, B30, B40, B50, B70, and B80). The results represent the average of three consecutive tests for each type of fuel evaluated. The diesel engine performed efficiently with all of the blends and with B100 without showing apparent damage.

As was observed in Figure 2, the addition of biodiesel in the formulations increases the consumption of fuel progressively. This increase is justified due to the smallest calorific power of biodiesel in relation to the reference diesel. According to the results, biodiesel increases the specific consumption by approximately 14%. This value is compatible with the difference in the enthalpy of combustion of diesel (44 MJ/kg) compared to that of fat biodiesel (37.5 MJ/kg).

4. Conclusions

The transesterification reaction of bovine fat with methanol in this work presented a conversion efficiency of approximately 95% of the FAMEs. The characterization of the raw material and biodiesel demonstrated that these present a larger concentration of saturated fatty acids with a predominance of stearic acid (C18:0). Consequently, these methyl esters produced from this raw material have larger stability to the oxidation as compared to the esters from vegetable oils.

The assessment of the chemical and physical properties demonstrated that this biodiesel presents characteristics similar to those of mineral diesel, and many of them are in agreement with the established limits by the ANP for petroleum diesel.

The tests carried out in an engine powered generator showed that biodiesel and its blends with diesel have higher specific fuel consumption than does pure diesel fuel, used as a reference.

In agreement with all the tests accomplished in this study, it is possible to affirm that the bovine fat biodiesel presents satisfactory fuel properties. According to the physicochemical properties measured for the biodiesel fabricated with beef tallow, it can be used as an alternative to petroleum diesel without needing modifications in the engine. The major benefit in using this biodiesel is the important reduction in emission of gas and particulate material contaminants at a cost increasingly affordable to the users.

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