The Kinematic Viscosity of Biodiesel and Its Blends with Diesel Fuel

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ABSTRACT: As the use of biodiesel becomes more widespread, engine manufacturers have expressed concern about biodiesel's higher viscosity. In particular, they are concerned that biodiesel may exhibit different viscosity–temperature characteristics that could result in higher fuel injection pressures at low engine operating temperatures. This study presents data for the kinematic viscosity of biodiesel and its blends with No. 1 and No. 2 diesel fuels at 75, 50, and 20% biodiesel, from close to their melting point to 100°C. The results indicate that while their viscosity is higher, biodiesel and its blends demonstrate temperature-dependent behavior similar to that of No. 1 and No. 2 diesel fuels. Equations of the same general form are shown to correlate viscosity data for both biodiesel and diesel fuel, and for their blends. A blending equation is presented that allows the kinematic viscosity to be calculated as a function of the biodiesel fraction.

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KEY WORDS: Biodiesel, diesel fuel, kinematic viscosity, methyl esters, methyl soyate, viscosity.

Biodiesel has come to be defined as the alkyl monoesters of fatty acids derived from vegetable oils or animal fats. The most prevalent form of biodiesel in the United States is produced by transesterifying soybean oil with methanol and is known as methyl soyate.

Biodiesel is receiving increasing attention as an alternative fuel for diesel engines. Biodiesel provides exhaust emission benefits compared to diesel fuel (1,2), but perhaps its greatest benefit is that it can be used in existing engines without modification. Further, it requires no changes to the existing fuel distribution and storage infrastructure. One concern about biodiesel is that its viscosity tends to be higher than that for diesel fuel. No. 2 diesel fuel has a viscosity in the range of 2.5–3.2 cSt at 40°C, and biodiesel consisting of the methyl esters of soybean oil has a viscosity between 4.2 and 4.6 cSt (1,3–6). Biodiesel viscosity is outside the range allowed by ASTM standard D975, which defines the properties of the different grades of diesel fuel (7). The viscosity of other types of biodiesel, such as the ethyl esters of rapeseed oil, have been reported to be as high as 6.0 (8).

Diesel engine company representatives have also expressed concern about whether the viscosity of biodiesel increases greatly at low temperatures. High viscosity could cause excessive fuel injection pressures during engine warm-up. The engine could also be starved for fuel at low temperatures as the fuel moves slowly through the fuel filter and fuel lines.

Data are presented here for the kinematic viscosity of biodiesel and its blends with No. 1 and No. 2 diesel fuels over the temperature range from the onset of crystallization to 100°C. Although the actual viscosity of biodiesel depends on the fatty acid composition of the oil or fat from which it is made, and also on the extent of oxidation and polymerization of the biodiesel, the data show the general behavior that can be expected of this fuel. Further, general equations that can be used to correlate viscosity data for biodiesel and its blends are presented. A blending equation is also shown that can be used to calculate the viscosity of mixtures of biodiesel and diesel fuel from the viscosities of the neat fuels.

MATERIALS AND METHODS

In this study, commercially available biodiesel (NOPEC Corporation, Lakeland, FL) was used, and its properties are as follows: carbon, 76.14%; hydrogen, 11.75%; sulfur, < 0.005%; heat of combustion, 37,272 kJ/kg; free glycerin, 0.002%; triglycerides, 0.140%; diglycerides, 0.125%; monoglycerides, 0.432%; total glycerin, 0.147%; palmitic acid, 10.83%; stearic acid, 4.31%; oleic acid, 24.22%; linoleic acid, 54.67%; linolenic acid, 6.78%; vitamin E (IU/kg), 16.09; cetane number, 51.1. Commercial grades of No. 1 and No. 2 diesel fuel were obtained from local fuel suppliers and their properties are given in Table 1. Blends of 20, 50, and 75% biodiesel with No. 1 and No. 2 diesel fuels were prepared by weight.

The Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids, ASTM Standard D445-88 (9), was used to measure the viscosity of the samples. This test method is commonly used to measure the kinematic viscosity of liquid petroleum products. The kinematic viscosity is determined by measuring the time for a known volume of liquid flowing under gravity to pass through a calibrated glass capillary viscometer tube. The manufacturer of the Cannon-Fenske type viscometer tubes supplied calibration constants at 40 and 100°C. These constants were generally different by approximately 0.5%, probably due to dimensional changes in

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TABLE 1
Physical and Chemical Properties of the Diesel Fuels Used

Properties	No. 1 diesel	No. 2 diesel
Carbon (%)	86.31	86.23
Hydrogen (%)	13.27	13.14
Sulfur (%)	0.039	0.034
Heat of combustion (kJ/kg)	42992	42715
Specific gravity	0.83	0.8428
Aromatics (%)	27.7	31.0
Paraffin (%)	69.7	64.1
Olefin (%)	2.6	4.9
Distillation (% recovered)[a]		
IBP	165°C	185°C
5%	187.2°C	207.2°C
10%	193.8°C	219.16°C
20%	202.2°C	231.6°C
30%	211.2°C	239.4°C
40%	219.4°C	247.7°C
50%	227.7°C	255.5°C
60%	236.6°C	263.8°C
70%	247.7°C	273.8°C
80%	260°C	285°C
90%	280°C	301.6°C
95%	297.7°C	315°C

[a] Fuel must be heated to the temperature shown to vaporize the specified percentage of fuel. IBP, initial boiling point.

the tubes at different temperatures. The kinematic viscosity values at each temperature were determined by multiplying the measured efflux time by a calibration factor that was linearly interpolated or extrapolated from the values at 40 and 100°C.

To cover the entire temperature range from the onset of crystallizaton of the esters to 100°C, the measurements were done in three steps. For the first step, data were collected from 20 to 100°C. For this range, a Precision Scientific (Chicago, IL) Kinematic Viscosity Bath with ±0.01°C temperature control was used. For the second step, data were collected from 0 to 20°C. While taking these data, a Haake (Saddle Brook, NJ) A81 temperature-controlled cooling bath, also with ±0.01°C temperature control, was connected to the Precision Scientific Kinematic Viscosity Bath's cooling coil to lower the temperature in the bath. To achieve temperatures below 0°C, it was necessary to use the Haake A81 cooling bath to provide a flow of controlled temperature fluid to a large open-mouth glass vessel containing the viscometer. Coolant (ethylene glycol antifreeze) was pumped from the reservoir into the jar and allowed to overflow from the vessel back into the bath.

According to the ASTM standard, in order to accept a viscosity measurement, the measurement should be conducted twice and the first and second measurements should be within a 0.02 cSt tolerance. This procedure was followed, and if a third measurement was needed, it was performed, and the readings in the tolerance band were averaged. This procedure also provided an effective means for the detection of the onset of crystallization. As the fuel started to crystallize, it was impossible to obtain a repeatable viscosity. This usually occurred before the crystallization could be detected visually.

RESULTS AND DISCUSSION

Figure 1 shows the kinematic viscosity of the biodiesel blends with No. 2 diesel fuel, and Figure 2 shows the kinematic viscosity for the blends with No. 1 diesel fuel. The measurements indicate that all the fuels have the same qualitative behavior, even at temperatures approaching the onset of crystallization. From the figures it is seen that the viscosity rapidly increases as the temperature decreases, and the viscosity of the blends varies between biodiesel and the diesel fuels according to their percentages. When we compare the viscosities shown in the two figures, the viscosity difference between the blends with No. 2 diesel fuel is less than for the blends with No. 1 diesel fuel because No. 2 diesel fuel is closer to the viscosity of biodiesel than No. 1 diesel fuel.

In Figures 1 and 2, the symbols correspond to the measured data points and the lines come from regression equations. The regression equation used was a commonly recommended equation cited in the literature (4,6),

$$\ln \eta = A + \frac{B}{T} + \frac{C}{T^2} \qquad [1]$$

where A, B, and C are constants for the fluid, T is the temperature in K, and η is the kinematic viscosity in cSt (mm^2/s). This

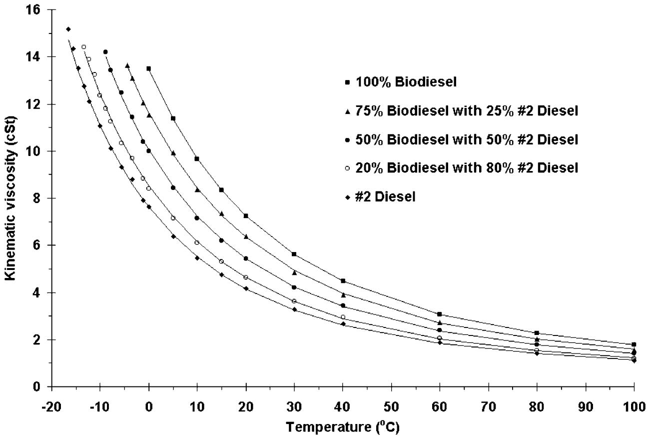

FIG. 1. Kinematic viscosities of biodiesel and its blends with No. 2 diesel fuel.

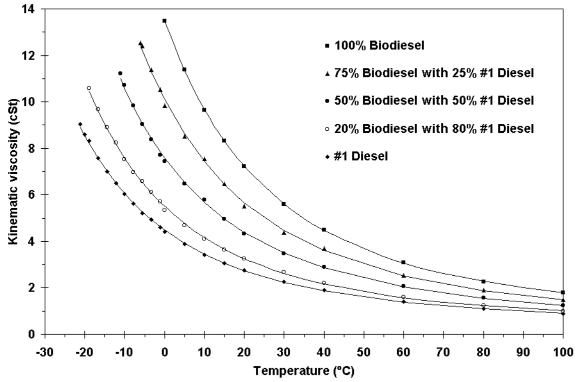

FIG. 2. Kinematic viscosities of biodiesel and its blends with No.1 diesel fuel.

TABLE 2
Viscosity Correlation Coefficients (Eq. 1) and Statistics[a]

Fuel Type	A	B	C	R^2	MSD	T_{MIN}, °C
100% biodiesel	0.7883	-1.638×10^3	5.825×10^5	0.9999	0.0004	0.0
75% biodiesel with #2 diesel	0.3733	-1.433×10^3	5.467×10^5	0.9998	0.0035	−4.4
50% biodiesel with #2 diesel	1.3314	-2.095×10^3	6.452×10^5	0.9998	0.0055	−8.9
20% biodiesel with #2 diesel	1.1583	-2.073×10^3	6.399×10^5	0.9997	0.0061	−10.0
#2 diesel	1.5029	-2.316×10^3	6.722×10^5	0.9997	0.0047	−14.4
75% biodiesel with #1 diesel	0.1808	-1.283×10^3	5.097×10^5	0.9995	0.0063	−6.1
50% biodiesel with #1 diesel	0.1322	-1.284×10^3	4.922×10^5	0.9996	0.0054	−7.8
20% biodiesel with #1 diesel	0.3564	-1.492×10^3	5.081×10^5	0.9996	0.0037	−18.9
#1 diesel	0.1539	-1.362×10^3	4.725×10^5	0.9998	0.0013	<−20

[a] MSD, mean square deviation; TMIN, lowest temperature for repeatable viscosity measurements.

equation can be considered to be a second-order polynomial in $1/T$, and the values of A, B, and C can be found using common polynomial curve-fitting software. The constants A, B, and C are given in Table 2 for the fuels and blends. It is clear from the correlation coefficients given in Table 2 that Equation 1 fits the data so well that it is not necessary to use higher-order equations. The lowest R^2 value was 0.9995 for all the fuels. Table 2 also shows the mean square deviations for the correlations and the lowest temperature at which repeatable viscosity data could be collected before the onset of crystallization. The correlations are valid from this temperature to 100°C.

A mixing equation similar in form to one originally proposed by Arrhenius and described by Grunberg and Nissan (10), was applied to the measured biodiesel and the No. 2 and No. 1 diesel fuel data to correlate the kinematic viscosities of the 75, 50, and 20% biodiesel blends with No. 2 and No. 1 diesel fuels. The general form of the equation was:

$$\log \eta_B = m_1 \log \eta_1 + m_2 \log \eta_2 \qquad [2]$$

where η_B is the kinematic viscosity of the blend, m_1 and η_1 are the mass fraction and the viscosity of component 1, and m_2 and η_2 are the mass fraction and viscosity of component 2. The original Arrhenius equation used mole fractions as the weighting factors on the viscosities. Mass fractions were used here because they are usually more readily available. The agreement between the measured data for the blends and the values obtained from Equation 2 is presented in Figure 3 and can be seen to be excellent. The maximal difference between the predicted viscosities and the measured data is less than 1.47% of the measured values for the 75% blend, 2.05% for the 50% blend, and 2.00% for the 20% biodiesel blend with No. 2 diesel fuel. Equation 2 gave maximal differences of less than 3.66, 3.74, and 3.39% of the measured values for 75, 50, and 20% biodiesel blends with No. 1 diesel fuel, respectively, at the temperatures where data were available. The mean square deviations of the measured data from the mixing rule were as follows: 75% biodiesel with #2 diesel, 0.0049 MSD; 50% biodiesel with #2 diesel, 0.0069; 20% biodiesel with #2 diesel, 0.0026; 75% biodiesel with #1 diesel, 0.0214; 50% biodiesel with #1 diesel, 0.0136; 20% biodiesel with #1 diesel, 0.0075. The deviations are smaller for the mixtures with No. 2 diesel fuel, and this is probably due to its viscosity being closer to that of biodiesel.

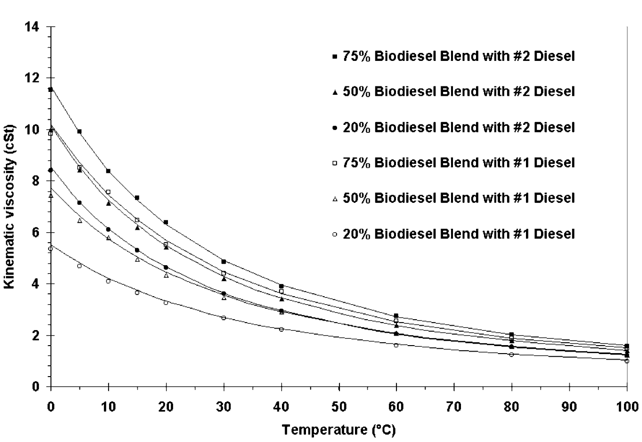

FIG. 3. Comparison of the results obtained by means of mixing equation with measured viscosity values for the blends with No. 2 and No. 1 diesel fuels. Symbols correspond to data points, and the lines are from Equation 2.

REFERENCES

1. Graboski, M.S., and R.L McCormick, Combustion of Fat and Vegetable Oil Derived Fuels in Diesel Engines, *Prog. Energy Combust. Sci. 24:*125–164 (1998).
2. Zhang, Y., Emissions and Combustion of Fatty Acid Esters of Soybean Oil in a Diesel Engine, M.S. Thesis, Iowa State University, Ames, Iowa, 1994.
3. Clements, D.L., Blending Rules for Formulating Biodiesel Fuel. Liquid Fuels and Industrial Products from Renewable Resources, in *Proceedings of the Third Liquid Fuel Conference,* American Society of Agricultural Engineers, Nashville, Sept. 15–17, 1996, pp. 44–53.
4. Gouw T.H., J.C. Vlugter, and C.J.A. Roelands, Physical Properties of Fatty Acid Methyl Ester. VI. Viscosity, *J. Am. Oil Chem. Soc. 43:*433–436 (1966).
5. Noureddini, H., B.C. Teoh, and D.L. Clements, Viscosities of Vegetable Oils and Fatty Acids, *Ibid. 69:*1189–1191 (1992).
6. Valeri, D., and A. Meirelles, Viscosities of Fatty Acids, Triglycerides, and Their Binary Mixtures, *Ibid. 74:*1221–1226 (1997).
7. ASTM D 975-97, *Standard Specifications for Diesel Fuel Oils,* American Society for Testing and Materials, Philadelphia, 1998.
8. Peterson, C.L., G.L. Wagner, and D.L. Auld, Vegetable Oil Substitutes for Diesel Fuel, *Trans. ASAE 26:*322–332 (1983)
9. ASTM D 445-88, *Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and the Calculation of Dynamic Viscosity),* American Society for Testing and Materials, Philadelphia, 1986.
10. Grunberg, L. and A.H. Nissan, Mixture Law for Viscosity, *Nature 164:*799–800 (1949).

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