Rheological Characterization of Yellow Grease and Poultry Fat

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ABSTRACT: The rheological properties of yellow grease and poultry fat and their liquid density at 25.0°C were experimentally determined. Dynamic viscosities of these industrial recycled fat products were measured for shear rates of 0.65 to 32.34 s^{-1} at temperatures of 15.6 to 71.1°C. The resulting measurements were fitted to a power law model to obtain values for the consistency coefficient and the flow behavior index. The data was also fit to Andrade's equation to relate viscosity to temperature. These results indicated pseudoplastic flow behavior for both products, with increasing non-Newtonian behavior at higher temperatures and shear rates.

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KEY WORDS: Biodiesel, chicken fat, fatty acids, poultry fat, recycled fats, rheology, shear rate, triglycerides, viscosity, yellow grease.

The development of value-added products from waste fats and oils provides expanded markets for producers of these by-products. These waste oils are generally disposed of at a cost to the producer or sold at low cost. The implementation of a beneficial and profitable recycling program for these wastes would both help reduce pollution from the disposal of these oils and generate additional income. One such value-added use for these oils is their implementation as biofuels or fuel extenders in traditional liquid fuel systems such as oil heaters or diesel engines. The use of waste fats and oils as alternative fuel sources or fuel extenders may provide an inexpensive fuel source while increasing the value of these by-products. In addition, the renewability of this biofuel gives it a competitive advantage over fossil fuels. Furthermore, these oils are sulfur-free and exhibit much lower particulate matter and CO emissions (1).

To implement value-added waste oil recycling systems on a large scale, it is necessary to determine the rheological behavior of these substances to guide the design of systems that will transport and utilize these oils. Since these fats exhibit high viscosity at room temperature, it is necessary to design systems with heating capabilities to ensure the flow of the fats. This study provides data necessary to help determine the environmental conditions in which these fats can be used as liquid fuels. This work examines the rheological properties of two typical waste fats: yellow grease and poultry fat. Yellow grease is a common industrial fat product traditionally sold at a low cost or simply disposed of at a cost to the producer. The poultry fat used in this study is a higher grade of recycled fat than yellow grease. These substances were selected to approximate the rheological behavior of common waste fats. The data collected on these products are compared to diesel fuel which, for our purposes, serves as a standard liquid fuel. This study will provide general parameters to guide the design and development of systems to use these recycled fats.

The dynamic viscosity of any fluid is equal to the ratio of the shear stress to the applied shear rate (γ). For Newtonian fluids this ratio is a constant, and the viscosity does not depend on the shear rate. Many fluids exhibit non-Newtonian viscosity behavior, which is a function of the applied shear rate. A general model to characterize the rheology of such fluids is given by a simple power law equation (2,3):

$$\eta = K\gamma^{n-1} \qquad [1]$$

where η is the apparent dynamic viscosity at a given temperature. A flow behavior index (n) less than unity indicates pseudoplastic behavior; an index greater than unity corresponds to dilatant behavior. Newtonian fluids have a flow behavior index of unity, which indicates that for these fluids the apparent viscosity remains constant for different shear rates. The parameter K is the consistency coefficient, a value that is proportional to the fluid's viscosity. Since viscosity is a function of temperature, the values of the two parameters (K and n) may also change with temperature. Therefore, K and n are determined experimentally from isothermal viscosity and shear rate data. Equation 1 often can be used to describe the rheology of non-Newtonian fluids and provides a simple model for this behavior when compared to other, more complex models such as those proposed by Lang *et al.* (4) and Toro-Vazquez and Infante-Guerrero (5), which have been used in the past to predict viscosity with high accuracy.

As the power law only addresses the dependence of viscosity on shear rate, other analysis is needed to address the issue of viscosity dependence on temperature. To correlate viscosity to temperature, Andrade's equation can be employed:

$$\eta = De^{B/T} \qquad [2]$$

where D and B are empirical constants and T is absolute temperature (6). This analysis is performed by measuring viscosity changes with varying temperature at a constant shear rate.

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A regression is then performed on these data to determine the constants D and B. The resulting equation provides a close approximation of viscosity as a function of temperature below the normal boiling point of the liquid (7). Generally, viscosity for a liquid decreases as temperature increases. This is attributable to a reduction in cohesive forces between the molecules in the liquid as temperature increases (6).

EXPERIMENTAL PROCEDURES

Poultry fat and yellow grease samples. Poultry fat and yellow grease were obtained from American Protein Co. (Cummings, GA). The samples were delivered on June 6, 2001, and all research was concluded by June 15, 2001. The yellow grease used in this study had a white precipitate at room temperature that was not present when the grease was heated to 71.1°C.

Density measurements. Atmospheric liquid density was calculated by measuring sample mass in a 100-mL graduated cylinder. The density at various temperatures was determined by measuring the volumes of the initial samples at different temperatures. Results obtained at 4.4 and 15.6°C had a possible error of ±0.04 g/mL for poultry fat and an error of ±0.01 g/mL for yellow grease due to the difficulty in measuring the volume of the semisolid fats.

Viscosity measurements. Viscosity was measured for each liquid sample in triplicate by using a Brookfield Synchrometric LVT viscometer with UL adapter (Stoughton, MA). This immersion-type concentric cylinder viscometer generated eight discrete shear rates between 0.32 and 64.69 s^{-1}. The instrument's accuracy and reproducibility were 1 and 0.2% of full scale, respectively. Observations that fell below 5% of full scale at a given shear rate were not within the instrument's range and therefore were not recorded. A circulating water bath provided five constant temperatures for experimentation: 4.4, 15.6, 23.9, 37.8, and 71.1°C. During a series of viscosity measurements, the four lowest temperatures (i.e., 4.4, 15.6, 23.9, 37.8°C) were maintained to an accuracy of ±0.1°C by calibration with an ASTM 63C standard thermometer. The highest temperature (71.1°C) was maintained to an accuracy of ±0.5°C.

FA analysis. FA analysis was performed by Woodson Tenent Labs (Memphis, TN) using GC (AOCS method Ce 2-66/Ce 1-62; 8). This method has an accuracy of 0.01%.

Determination of empirical constants. The flow behavior index (n) and consistency coefficient (K) were determined with TK Solver software (UTS Rockford, ID) using the iterative solver routine. Results were verified using the graphical data analysis method described by Levenspiel (3). The empirical constants D and B in Andrade's equation were determined by graphical regression of the measured data using Microsoft Excel (Redmond, WA).

RESULTS AND DISCUSSION

Figure 1 shows the densities of poultry fat and yellow grease as a function of temperature. The liquid density of poultry fat at 23.9°C was measured to be 0.88 g/mL, and for yellow grease was 0.91 g/mL. These results are slightly higher than the density of diesel fuel, which was previously reported to be 0.8399 g/mL at 25.0°C (9). These data suggest that transport of these fats in fueling systems would require modification in systems that are designed to utilize diesel or other liquid fuels with similar density. The increased density would result in an elevated weight-to-volume ratio, which could be damaging to equipment designed to work with lighter fuels. To compensate for this, reinforcement of joints and supports may be necessary in some transport systems.

Figure 2 shows the apparent viscosities of poultry fat and yellow grease, respectively, as functions of shear rate for tem-

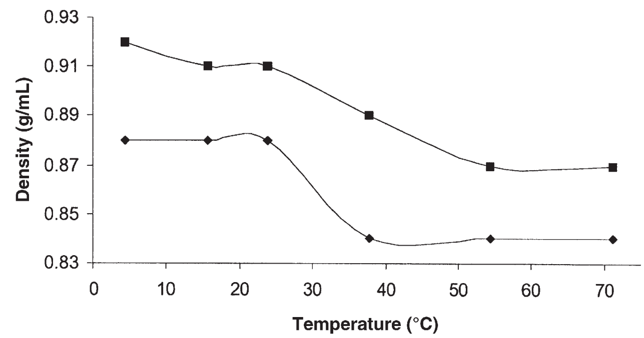

FIG. 1. Density vs. temperature for poultry fat (◆) and yellow grease (■). Continuous lines are connecting-point lines.

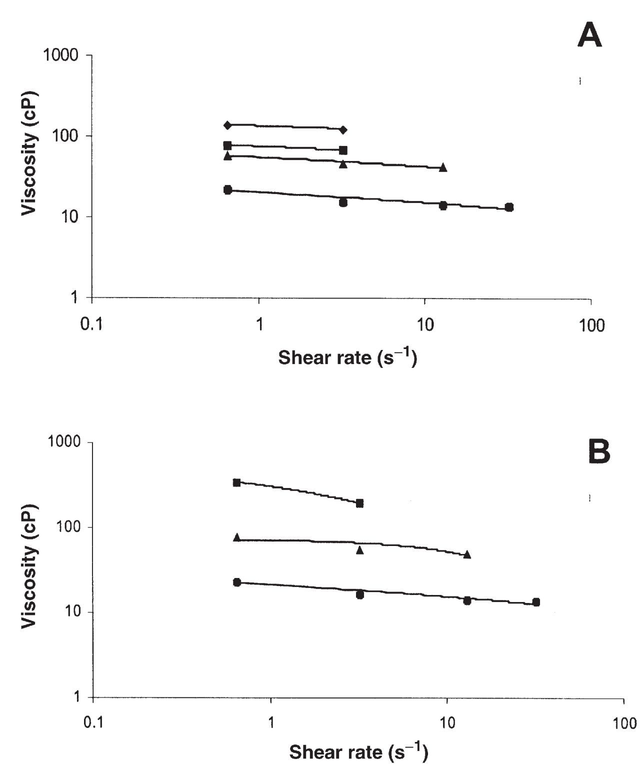

FIG. 2. Apparent dynamic viscosity of poultry fat (A) and yellow grease (B) vs. shear rate: 15.6°C, ◆; 23.9°C, ■; 37.8°C, ▲; 71.1°C, ●.

TABLE 1
Consistency Coefficient (*K*) and Flow Behavior Index (*n*) for Poultry Fat and Yellow Grease

	Poultry fat		Yellow grease	
Temperature (°C)	*K*	*n*	*K*	*n*
23.9	133.0	0.92	287.0	0.64
37.8	74.0	0.91	77.0	0.80
54.4	54.0	0.84	27.2	0.90
71.1	20.6	0.85	21.0	0.87

peratures of 15.6, 23.9, 37.8, and 71.1°C. Since yellow grease was a solid at the lowest temperature, its viscosity was not measured**.** The apparent viscosity of poultry fat ranged from 13.7 cP at the highest measured temperature (71.1°C) and highest measured shear rate (32.34 s^{-1}) to 138 cP at the lowest temperature (15.6°C) and lowest shear rate (0.65 s^{-1}). For yellow grease, the viscosity ranged from 13.7 cP at the highest measured temperature (71.1°C) and highest measured shear rate (32.34 s^{-1}) to 801 cP at the lowest temperature (15.6°C) and lowest shear rate (0.65 s^{-1}).

Figure 2 shows several characteristics of the rheological behavior. The apparent viscosity of both fats decreased with increasing shear rate, indicating pseudoplastic behavior. This shear thinning behavior is common in oils and some polymers (6). Also, as temperature increased, viscosity at a constant shear rate decreased dramatically. At 37.8°C, poultry fat had a viscosity of 41.9 cP and yellow grease had a viscosity of 48.4 cP at a shear rate of 12.94 s^{-1}. Increasing the temperature of these fats to 71.1°C resulted in a viscosity of 13.7 cP for both fats at a shear rate of 32.34 s^{-1}. This value approaches that of diesel fuel at 25°C, which has a viscosity of about 5.5 cP at a shear rate of 12.94 s^{-1} (9). Another important observation is that at the highest temperature (71.1°C) the viscosities of the two fats converged. At the lower temperatures yellow grease exhibited significantly higher viscosity than poultry fat. Yellow grease also had a white precipitate present at these temperatures, which was not present at 71.1°C. It is likely that the decrease in viscosity can be attributed to the melting of this precipitate resulting in a uniform liquid with rheology similar to the poultry fat studied here.

Table 1 shows values for the two parameters (*K* and *n*, respectively), resulting from regressions of each data set in Figure 2 to Equation 1. Since viscosity is proportional to the consistency coefficient (*K*), we again observe that the viscosity of these oils decreases as temperature increases, indicating shear-thinning behavior (6). Table 1 illustrates that poultry fat and yellow grease are both slightly pseudoplastic, having flow behavior indices (*n*) less than unity (3). As with viscosity, we see a convergence of the consistency coefficient and flow behavior index at the highest temperature (71.1°C). This non-Newtonian behavior is significant as, at lower temperatures, the flow behavior index for each substance reacted differently to changes in temperature. Poultry fat displayed a slight decrease in *n* as temperature increased, but yellow grease reacted inconsistently to temperature changes. As temperature increased, this variation became less significant. This, again, suggests that once the precipitate in the yellow grease melted, the rheology of the two fats became relatively indistinguishable.

Figure 3 shows plots of Andrade's equation at each shear rate, and Table 2 shows the empirical constants *D* and *B* determined for Equation 2 for each of the fat mixtures at constant shear rates. This analysis illustrates the temperature dependence of viscosity. The effect of elevated temperature is evident in Figure 3, as we can see a convergence of the plots as $1/T$ decreases, which is consistent with earlier observations where increased temperature resulted in a convergence of rheological properties. Interestingly, as shear rate increased, we began to see very little difference in these equations between shear rates. This is illustrated by the similarity of *D* and *B* for poultry fat at shear rates of 3.23 and 12.94 s^{-1}. The diminishing effects of high shear rates are also observed in Figure 2, where one can see viscosity leveling off as shear rate increases. At high shear rates, it appears that the rheology of these fats begins to resemble that of a Newtonian fluid, as viscosity becomes relatively shear independent.

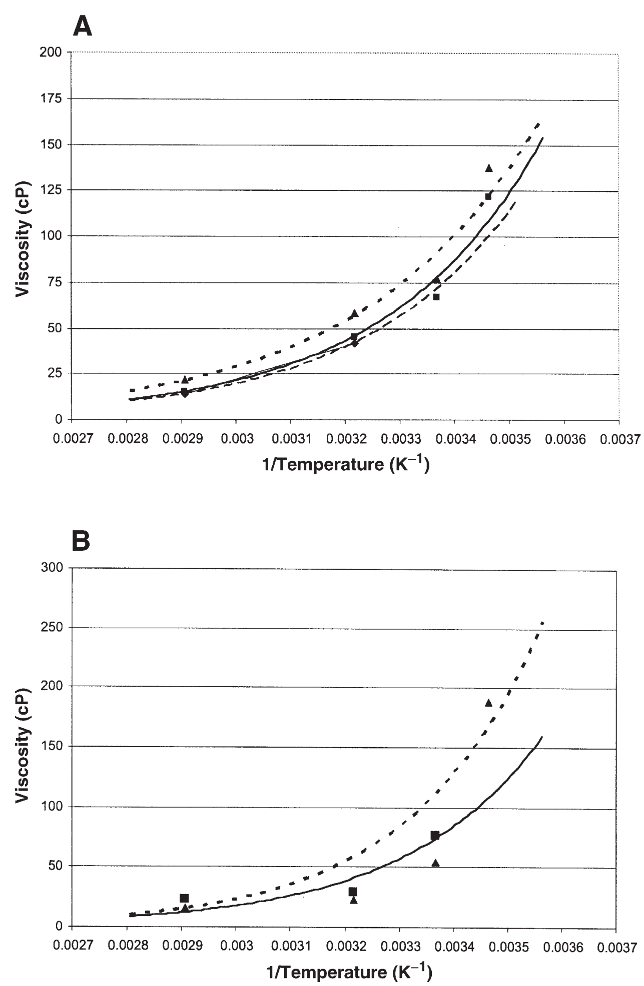

FIG. 3. Plots of Andrade's equation (Eq. 2) for poultry fat (A) and yellow grease (B) at various shear rates: 0.65 s^{-1}, - - -▲; 3.23 s^{-1}, —■; 12.94 s^{-1}, – –◆.

TABLE 2
Emperical Constants for Andrade's Equation

Substance	Shear rate (s^{-1})	D^a	B^a
Poultry fat	0.65	0.0026	3101.1
	3.23	0.0005	3523.2
	12.94	0.0005	3520.6
Yellow grease	0.65	0.0001	4224.8
	3.23	0.0001	3908.6

[a]Fitted to Equation 2: $\eta = De^{B/T}$.

TABLE 3
FA Composition of Poultry Fat and Yellow Grease

FA	Poultry fat (%)	Yellow grease (%)
C16:0	22.1	12.3
C16:1	7.45	1.13
C18:0	4.85	6.85
C18:1	39.2	36.5
C18:2	16.4	27.3
C18:3	1.01	2.62

Table 3 shows the FA compositions of the poultry fat and yellow grease studied here. The predominant component of both waste fats is oleic acid (C18:1). Significant variation occurs in the palmitic (C16:0) and linoleic (C18:2) fractions. The poultry fat has roughly twice the amount of C16:0 that yellow grease contains, whereas yellow grease has twice the amount of C18:2. This variation is representative of what one would expect to see in recycled fats from different sources. Previously reported chicken fat data from Lee and Foglia (10) show a FA profile very similar to our poultry fat, and data from Bartov *et al.* (11) provide evidence that diet can drastically affect the FA composition of chicken fat. It should be noted that the FA analysis performed here does not account for other impurities in these fat mixtures. The low quality of these products suggests that other contaminants (biological and otherwise) could be present and may ultimately affect overall viscosities.

The power law equation provided an accurate model of the rheological behavior of yellow grease and poultry fat. The behavior of both substances was pseudoplastic. This pseudoplastic behavior was very pronounced in yellow grease at low temperature, but was much less obvious in poultry fat and yellow grease at increased temperatures. The two fats had distinct rheological properties at lower temperatures, but their behaviors converged as temperature increased. This may have been attributable to the precipitate in yellow grease, which melted at the highest temperature studied here. The melting of the precipitate resulted in an entirely liquid fat with properties similar to the liquid poultry fat. Also, the behavior of these fats approached that of diesel fuel as temperature increased. This suggests that heating these fats would facilitate their use in a fuel system, such as diesel, that normally utilizes a liquid fuel as the primary fuel source.

The inherent compositional variation of waste animal fats derived from different sources will require systems that are designed to use these fuels to cope with varying physical properties such as viscosity. Our data show that heating these fat products not only decreases their individual viscosities but also brings the viscosities of two oils with distinct FA compositions within range of each other. This suggests heating the fats used in these systems may both reduce their viscosities to an acceptable level and reduce the variation seen at lower temperatures in these recycled products.

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