Effect of Temperature and Pressure on the Speed of Sound and Isentropic Bulk Modulus of Mixtures of Biodiesel and Diesel Fuel

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ABSTRACTS: The density and speed of sound of blends of biodiesel with No. 2 and No. 1 diesel fuels were measured from atmospheric pressure to 32.46 MPa at temperatures of 20 and 40°C. The isentropic bulk modulus was calculated from these quantities. The results show that the density and isentropic bulk modulus can be accurately modeled as having a linear variation with blend percentage. Speed of sound is better correlated by a second-order equation. Correlation equations are given and a blending rule is developed that allows the density, speed of sound, and isentropic bulk modulus of blends to be calculated from the properties of the biodiesel and diesel fuel.

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KEY WORDS: Alkyl esters, biodiesel, bulk modulus, compressibility, density, diesel engine, diesel fuel, fuel blends, physical properties, speed of sound.

Biodiesel is an environmentally friendly alternative diesel fuel that is obtained from vegetable oils, animal fats, and recycled restaurant grease. It is described in ASTM D 6751-02 as "a fuel comprised of mono-alkyl esters of long chain fatty acids derived from vegetable oils or animal fats" (1). One of the attractive characteristics of biodiesel is that its use does not require any significant modifications to the diesel engine, so the engine does not have to be dedicated for biodiesel use only. Biodiesel is completely soluble in diesel fuel, so it can be blended in any proportion with petroleum-based diesel fuel. The impact of the changes is usually proportional to the fraction of biodiesel being used. However, biodiesel has physical and chemical properties different from diesel fuel; higher density, higher viscosity, higher speed of sound, higher isentropic bulk modulus, lower heating value, higher cetane number, and lower volatility (2–4). These property changes affect both the fuel injection system and the diesel engine combustion, causing lower power and higher output of oxides of nitrogen. This paper is a companion to a report (5) on the speed of sound and isentropic bulk modulus of the pure esters that are the constituents of biodiesel. The objective of this study is to investigate the effect of biodiesel/diesel fuel blend level on the density, speed of sound, and isentropic bulk modulus at higher pressures and at temperatures of 20 and 40°C.

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MATERIALS AND METHODS

The ultrasonic pulse echo technique was used to measure the speed of sound in the fuel samples (6–8). A Panametrics Model 5072 PR general-purpose ultrasonic pulser/receiver and a Panametrics 10 MHz videoscan immersion transducer (Waltham, MA) were used. A pressure vessel with a piston-and-cylinder assembly for raising the pressure was fabricated, and the ultrasonic transducer was located at the bottom of the vessel in a hosing. The pressure vessel and the ultrasonic transducer housing were both submerged in an oil bath. The temperature of the fuel sample in the vessel was not measured. However, the temperature of the oil bath was controlled by using an Omega CN 9000A (Chicago, IL) temperature controller and a Fisher Scientific Isotemp Immersion Circulator Model 70 (Stamford, CT). Temperature was measured with a thermometer with ±0.5°C accuracy, and before each measurement 40 min of waiting time was taken for temperature equilibrium. This time was found to be adequate to provide a stable measurement. Signals were captured with a Hewlett-Packard Model 54601A 100 MHz, four-channel digital oscilloscope (Colorado Springs, CO). The system pressure was measured using a Sensotec Model 2 Z/1108-04Z9 pressure transducer (Columbus, OH). Elevated temperatures were obtained by submerging the entire pressure vessel in a temperature-controlled bath. The pressure vessel and associated equipment are described in Reference 4.

Density and speed of sound were measured in 100% biodiesel and commercial grades of No. 1 and No. 2 diesel fuels. The biodiesel for this project was prepared from soybean oil and methanol, and its properties were measured to confirm that it met the requirements of ASTM D 6751. Detailed information about the physical and chemical properties of the biodiesel and the diesel fuels is given in Table 1. Blends of 20, 50, and 75% biodiesel with the No. 1 and No. 2 diesel fuels were prepared by weight, and density and speed of sound were measured from atmospheric pressure to 32.46 MPa and at temperatures of 20 and 40°C. The isentropic bulk modulus, which is the inverse of the compressibility, was calculated at each pressure and temperature level using Equation 1 (9,10),

$$\beta = c^2 \times \rho \quad [1]$$

where β is the isentropic bulk modulus in Pa, c is the speed of sound in m/s, and ρ is the density in kg/m^3.

TABLE 1
Physical and Chemical Properties of Commercial No. 2 and No. 1 Diesel Fuels

Test property	Commercial no. 2 diesel fuel	Commercial no. 1 diesel fuel	Soy methyl ester
Carbon (% mass)	86.70[a]	86.83[a]	77.10[b]
Hydrogen (% mass)	12.71[a]	12.72[a]	11.81[b]
Oxygen (% mass)	—	—	10.97[b]
C/H Ratio	6.82	6.826	6.53
Sulfur (% mass)	0.041[a]	0.045[a]	<0.005[a]
Cetane number (ASTM D 613)	42.6[a]	45.3[a]	51.5[a]
Gross heat of combustion (kJ/kg)	45,339[a]	45,991[a]	39,871[a]
Net heat of combustion (kJ/kg)	42,640[a]	43281[a]	37,388[a]
Specific gravity (@21°C)	0.8537[c]	0.8162[c]	0.8814[c]
Kinematic viscosity (cSt @40°C)	2.827[c]	1.759[c]	4.299[c]
Total glycerin (% mass)	—	—	0.028[d]
Free glycerin (% mass)	—	—	0.000[d]
Distillation (ASTM D 86, °C)[a]			
Initial b.p. (%)	178	176	—
5	200	189	—
10	212	196	—
20	227	201	—
30	239	208	—
40	250	213	—
50	261	219	—
60	272	227	—
70	284	234	—
80	298	246	—
90	317	262	—
95	332	279	—
End point	345	304	—
Recovery (%)	98.0	98.0	—
Residue (%)	1.9	1.9	—
Loss (%)	0.1	0.1	—

[a]Measured by Phoenix Chemical Laboratory Inc. (Chicago, IL).
[b]Calculated from FA distribution.
[c]Measured in the Department of Mechanical Engineering, Iowa State University (Ames, IA).
[d]Measured by Williams Laboratory Services (Kansas City, KS).

The density was initially measured at atmospheric pressure and temperatures of 20 and 40°C with a specific gravity balance (Troemner Company, Philadelphia, PA) modified so that a constant temperature bath could control the sample temperature. A detailed explanation of this measurement is given in Reference 3. Four measurements were taken at each temperature level and repeated two times. Therefore, at atmospheric pressure, eight measurements were obtained. The balance was calibrated with distilled water to 1.0000 at 15.5°C before the measurements. At higher pressures, the density was calculated using the volume change of the pressure vessel at each pressure level for two filling and emptying operations, and two independent measurements were taken at each temperature level. Comparisons of pure compounds with published data have been made (5).

RESULTS AND DISCUSSION

The density, speed of sound, and isentropic bulk modulus of the fuel samples showed approximately linear increases with pressure at the two temperature levels, 20 and 40°C. A polynomial that was linear in temperature, pressure, and blend percentage was used to fit the density and isentropic bulk modulus data. This general equation is shown in Equation 2:

$$y = C_1T + C_2P + C_3B + C_4 \qquad [2]$$

where y is the density or the isentropic bulk modulus of the blends of No.1 and No. 2 diesel fuel with biodiesel fuel, T is the temperature in °C, P is the pressure in MPa, B is the biodiesel percentage in the blend, and C_i, where i = 1–4, are

TABLE 2
Density[a] Regression Constants

Samples	$C_1 \times 10^4$	$C_2 \times 10^4$	$C_3 \times 10^4$	$C_4 \times 10$	R^2	$SE_y \times 10^4$
No. 2 diesel fuel blends	2.6324	5.8574	–6.5302	8.6671	0.9983	5.5
No. 1 diesel fuel blends	5.9030	6.1040	–6.5757	8.3318	0.9991	7.2

[a]Density (g/cm^3) = $C_1 \times T$ (°C) + $C_2 \times P$ (MPa) + $C_3 \times B$ (biodiesel percentage) + C_4. SE_y, standard error for the y estimate.

TABLE 3
Isentropic Bulk Modulus[a] Regression Constants

Samples	C_1	$C_2 \times 10^{-1}$	C_3	$C_4 \times 10^{-3}$	R^2	SE_y
No. 2 diesel fuel blends	1.1927	1.2170	–9.7434	1.8384	0.9985	6.8
No. 1 diesel fuel blends	2.7763	1.2206	–9.6579	1.6727	0.9983	8.1

[a]Isentropic bulk modulus (MPa) $= C_1 \times T$ (°C) $+ C_2 \times P$ (MPa) $+ C_3 \times B$ (biodiesel percentage) $+ C_4$. For abbreviations see Table 2.

TABLE 4
Speed of Sound[a] Regression Constants

Sample	No. 2 blends	No. 1 blends
C_1	–3.5972	–3.7043
C_2	4.6849	5.0232
$C_3 \times 10$	2.3682	6.5479
$C_4 \times 10^2$	1.4412	1.4958
$C_5 \times 10^3$	–3.9664	–6.9146
$C_6 \times 10^2$	–1.6236	–1.7425
$C_7 \times 10^4$	8.8429	11.8120
$C_8 \times 10^{-3}$	1.4570	1.4147
R^2	0.9989	0.9990
SE_y	2.0	2.1

[a]Speed of sound (m/s) $= C_1 \times T$ (°C) $+ C_2 \times P$ (MPa) $+ C_3 \times B$ (biodiesel percentage) $+ C_4 \times T \times P + C_5 \times P \times B + C_6 \times P^2 + C_7 \times B^2 + C_8$. For abbreviations see Table 2.

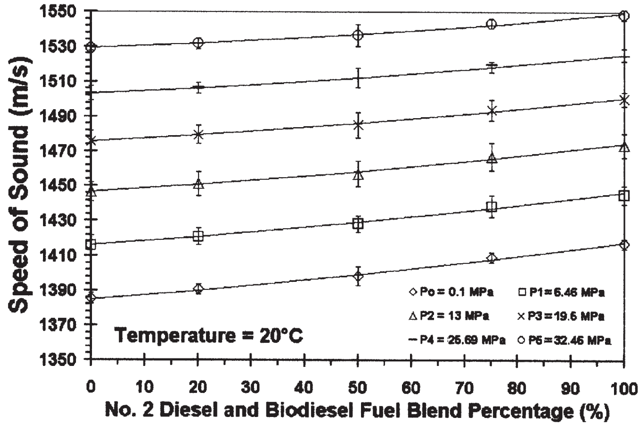

FIG. 2. Speed of sound comparison between measured data and regression equation [lines are from the three-variable regression (T, P, and B)]. For abbreviations see Figure 1.

the regression constants given in Tables 2 and 3. The R^2 values and the standard errors for y, calculated by an Excel spreadsheet, are also shown in the tables.

A more complex three-variable polynomial was used to fit the speed of sound data. The general form of this equation is shown in Equation 3:

$$y = C_1T + C_2P + C_3B + C_4TP + C_5PB + C_6P^2 + C_7B^2 + C_8 \quad [3]$$

The coefficients C_i, where $i = 1$–8, are given in Table 4. The density, speed of sound, and isentropic bulk modulus of the biodiesel–No. 2 diesel fuel blends at 20°C are presented in Figures 1–3, respectively. The data points shown on the figures are the averaged measured values at each pressure level, and the lines are the regression results calculated using Equations 2 and 3. Error bars represent 90% confidence intervals. As can be observed from the figures, the density and the isentropic bulk modulus show very nearly linear behavior with blend percentage at each pressure level. The speed of sound data were approximately linear with biodiesel percentage, but a higher degree polynomial provided better regression accuracy. The density, speed of sound, and isentropic bulk modulus data also showed very nearly linear behavior with pressure. Results at 40°C were similar to those at 20°C.

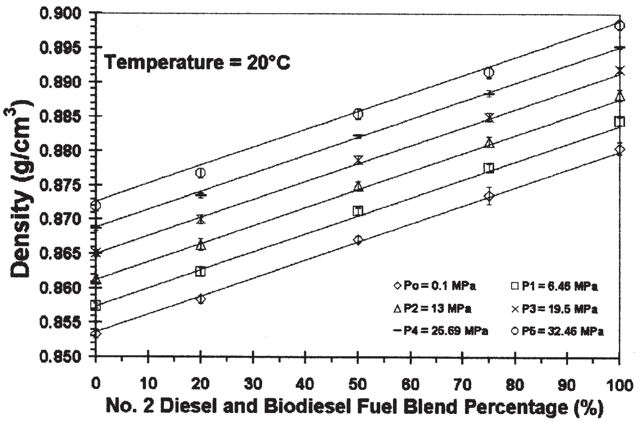

FIG. 1. Density comparison between measured data and regression equation [lines are from the three-variable regression: temperature (T), pressure (P), and biodiesel percentage (B)].

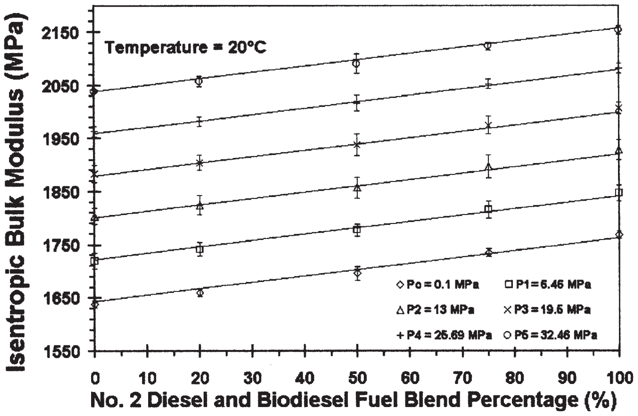

FIG. 3. Isentropic bulk modulus comparison between measured data and regression equation [lines are from the three-variable regression (T, P, and B)]. For abbreviations see Figure 1.

REFERENCES

1. Standard Specifications for BIODIESEL Fuel (B100) Blend Stock for Distillate Fuels, in *American Society for Testing and Materials*, Philadelphia, PA, 1998, ASTM D 6751-02.
2. Tat, M.E., and J.H. Van Gerpen, The Kinematic Viscosity of Biodiesel and Its Blends with Diesel Fuel, *J. Am. Oil Chem. Soc. 76*:1511–1513 (1999).
3. Tat, M.E., and J.H. Van Gerpen, The Specific Gravity of Biodiesel and Its Blends with Diesel Fuel, *Ibid. 77*:115–119 (2000).
4. Tat, M.E., J.H. Van Gerpen, S. Soylu, M. Canakci, A. Monyem, and S. Wormley, The Speed of Sound and Isentropic Bulk Modulus of Biodiesel at 21°C from Atmospheric Pressure to 35 MPa, *Ibid. 77*:285–289 (2000).
5. Tat, M.E., and J.H. Van Gerpen, Speed of Sound and Isentropic Bulk Modulus of Alkyl Monoesters at Elevated Temperatures and Pressures, *J. Am. Oil Chem. Soc.,* in press.
6. McClements J.D., and M.J.W. Povey, Ultrasonic Analysis of Edible Fats and Oils, *Ultrasonics 30*:383–387 (1992).
7. Kuo, H.-L., Variation of Ultrasonic Velocity and Absorption with Temperature and Frequency in High Viscosity Vegetable Oils, *Jpn. J. Appl. Phys. 10*:167–170 (1971).
8. McClements J.D., and M.J.W. Povey, Ultrasonic Velocity Measurements in Some Liquid Triglycerides and Vegetable Oils, *J. Am. Oil Chem. Soc. 65*:1787–1790 (1988).
9. Boelhouwer, J.W.M., Sound Velocities in and Adiabatic Compressibilities of Liquid Alkanes at Various Temperatures and Pressures, *Physica 34*:484–492 (1967).
10. Rolling, R.E., and C.J. Vogt, The Adiabatic Bulk Modulus of Normal Paraffin Hydrocarbons from Hexane to Hexadecane, *Trans. ASME–J. Basic Eng. 82*:635–644 (1960).

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