

Compressed-Liquid Density Measurements of Methyl Oleate and Methyl Linoleate

Stephanie L. Outcalt*

Material Measurement Laboratory, Thermophysical Properties Division, National Institute of Standards and Technology (NIST), 325 Broadway Boulder, Colorado 80305-3337, United States

ABSTRACT: Compressed-liquid densities of the fatty acid methyl esters (FAMES) methyl linoleate and methyl oleate have been measured with a vibrating-tube densimeter. The temperature and pressure ranges of the measured data are from (270 to 470) K and (0.5 to 50) MPa. The data at 10 MPa and below have been extrapolated to 0.083 MPa (the approximate ambient pressure in Boulder, CO) for comparison with existing literature data. A correlation is given that represents the temperature and pressure dependence of the reported experimental data within their estimated uncertainties.

1. INTRODUCTION

Fatty acid methyl esters (FAMES) include compounds that have a wide scope of applications from the perfume and food industries to being some of the major components of biodiesel fuels. In the production of biodiesel fuel, oil produced from the feedstock is chemically modified through a process called transesterification, which substitutes a simple alcohol, such as methanol, for the complex alcohol, glycerol. The products of this process are primarily FAMES, and the process results in a material with a lower viscosity that is more suitable for fuel than the oil derived from the feedstock. Some of the advantages of biodiesel fuels include the following: it is renewable, it is energy-efficient, it displaces petroleum-derived diesel fuel, it can be used as a 20 % blend in most diesel equipment with no or only minor modifications, and it can reduce global warming gas emissions.¹

The rising price and unreliable supply of petroleum are galvanizing the search for renewable fuels that can be used within existing infrastructure with few modifications. Biodiesel fuel is a viable candidate, but more research is necessary to understand the full potential of a variety of feedstocks and the characteristics of the resulting fuels. Five fatty acid methyl esters have been found to make up the majority of the components present in biodiesel fuel derived from the majority of current biodiesel fuel feedstocks. Methyl linoleate (CAS Registry No. 112-63-0) and methyl oleate (CAS Registry No. 112-62-9) are the two most important of those five FAMES.² Measured compressed-liquid densities of methyl linoleate and methyl oleate from (270 to 470) K and (0.5 to 50) MPa are reported here. The major goal of the measurements reported here is to provide data that are lacking in the literature and thus enable the formulation of more accurate equations of state. Pure fluid equations can then be used in combination to build surrogate mixture models for such complex fluids as the biodiesel fuels.³ These models can then serve as tools to aid in the design of new equipment and new fuel formulations to increase efficiency.

2. SAMPLE LIQUID

The samples measured in this work were purchased from Sigma-Aldrich Corporation (To describe materials and experimental

procedures adequately, it is occasionally necessary to identify commercial products by manufacturers' names or labels. In no instance does such identification imply endorsement by the National Institute of Standards and Technology, nor does it imply that the particular product or equipment is necessarily the best available for the purpose). Both the methyl linoleate and the methyl oleate were specified by the manufacturer as being greater than 99 % pure. Analyses of the samples were performed in our laboratory by gas chromatography–flame ionization detection (GC-FID) on a 30 m capillary column with a 0.1 mm coating of 50 % cyanopropyl/50 % dimethylpolysiloxane as the stationary phase. This phase provides separations based upon polarity and is specifically intended for the analysis of the FAMES that compose biodiesel fuel. Details of the analysis technique are given in Smith et al.⁴ and Bruno and Svoronos.⁵ Both samples were found to be within manufacturer specifications and showed no detectable impurities.

A small amount of inhibitor (*tert*-butylhydroquinone, TBHQ) was added to both samples to avoid the possibility of chemical decomposition at higher temperatures. The amount of TBHQ added to the methyl linoleate sample was 0.16 % by weight and 0.09 % for the methyl oleate. TBHQ has a higher density than that of either methyl linoleate or methyl oleate. As such, the effect of the addition of TBHQ to our samples would have increased the values of our measured densities. The density of TBHQ at 298.15 K is approximately 1050 kg·m⁻³, while methyl linoleate and methyl oleate have densities of approximately 881 kg·m⁻³ and 870 kg·m⁻³ at that temperature. As such, the addition of the TBHQ could have potentially raised the densities of our measured values of methyl linoleate by up to 0.3 kg·m⁻³ and those of methyl oleate by as much as 0.2 kg·m⁻³.

3. EXPERIMENTAL SECTION

The densities of the compressed test liquids were measured with the automated densimeter of Outcalt and McLinden.⁶ Central to the apparatus is a commercial vibrating-tube densimeter. Several

Received: August 1, 2011

Accepted: September 15, 2011

Published: September 30, 2011

physical and procedural improvements have been implemented beyond that of the commercial instrument operated in a stand-alone mode to minimize the uncertainty in the measurements. Some of these improvements include more accurate measurements of temperature and pressure, better temperature control, and complete automation of the instrument control and data acquisition. The temperature range of the instrument is (270 to 470) K with pressures up to 50 MPa. In this work, we measured 11 isotherms over the range (0.5 to 50) MPa for each of the samples. The instrument was calibrated with propane and toluene over the entire temperature and pressure range. Further details of the calibration procedure can be found in Outcalt and McLinden.⁶ The overall combined uncertainty ($k = 2$) in density is at most $0.81 \text{ kg} \cdot \text{m}^{-3}$, corresponding to a relative uncertainty in density of 0.09 % to 0.11 %. The addition of the TBHQ to the methyl linoleate and methyl oleate samples is not expected to have changed the overall uncertainty of the measurements, but rather to have added a positive bias to the measurements of approximately $0.3 \text{ kg} \cdot \text{m}^{-3}$.

4. RESULTS AND CORRELATIONS

Tables 1 and 2 list the measured density values of the compressed-liquids methyl linoleate and methyl oleate from (270 to 470) K to pressures of 50 MPa, respectively. The tables include density values extrapolated to the local ambient pressure of 0.083 MPa at each temperature. The extrapolated data were obtained by fitting second-order polynomials to the isothermal densities at pressures less than or equal to 10 MPa and then calculating the densities at 0.083 MPa from the polynomials. To compare our data to the ambient pressure data found in the literature, the extrapolated data were correlated with a Rackett-type equation:

$$\rho = \beta_1 \cdot \beta_2^{-(1 + (1 - T/\beta_3)^{\beta_4})} \quad (1)$$

The parameters for eq 1 are listed in Table 3. The critical temperatures of methyl linoleate (767.4 K) and methyl oleate (764.0 K) as found in the DIPPR database⁷ were used as the value of the β_3 parameter. The values were taken from Lydersen⁸ and were estimated by Lydersen's method, based on a predicted boiling point. The average absolute deviation (AAD) of our extrapolated data from the correlation is 0.02 % for methyl linoleate and 0.01 % for methyl oleate.

A survey of the literature for ambient pressure density data found twelve sources of data on methyl linoleate^{2,9–19} and nine sources for methyl oleate.^{2,19–26} The data sets of Ott et al.² and Pratas et al.¹⁹ represent the majority of the available data, while many of the sources represent only one or two data points. This is especially true for methyl linoleate. Figure 1a,b shows deviations of our extrapolated data and the literature data from our correlations for methyl linoleate and methyl oleate, respectively. Also shown in the figures are the deviations of the correlations for saturated liquid densities given in the NIST Standard Reference Database 23 (REFPROP)²⁷ and the DIPPR⁷ database. Both parts of Figure 1, a and b, illustrate that our extrapolated densities are slightly larger than the majority of the literature data and generally agree within 0.2 %. Error bars showing the uncertainty bounds of our data (± 0.1 %) and the data of Ott et al. (± 0.1 %) are shown in both figures at points around 310 K to help indicate agreement between the two data sets within their combined uncertainties. As mentioned previously, the addition of the TBHQ to both the methyl linoleate and methyl oleate samples would have increased

Table 1. Compressed-Liquid Densities of Methyl Linoleate Measured in the High Pressure Vibrating-Tube Densimeter along Isotherms from (270 to 470) K^a

270 K		290 K		310 K		330 K		350 K		370 K		390 K		410 K		430 K		450 K		470 K	
pressure	density	pressure	density	pressure	density	pressure	density	pressure	density	pressure	density	pressure	density	pressure	density	pressure	density	pressure	density	pressure	density
<i>p</i>	ρ	<i>p</i>	ρ	<i>p</i>	ρ	<i>p</i>	ρ	<i>p</i>	ρ	<i>p</i>	ρ	<i>p</i>	ρ	<i>p</i>	ρ	<i>p</i>	ρ	<i>p</i>	ρ	<i>p</i>	ρ
MPa	$\text{kg} \cdot \text{m}^{-3}$	MPa	$\text{kg} \cdot \text{m}^{-3}$	MPa	$\text{kg} \cdot \text{m}^{-3}$	MPa	$\text{kg} \cdot \text{m}^{-3}$	MPa	$\text{kg} \cdot \text{m}^{-3}$	MPa	$\text{kg} \cdot \text{m}^{-3}$	MPa	$\text{kg} \cdot \text{m}^{-3}$	MPa	$\text{kg} \cdot \text{m}^{-3}$	MPa	$\text{kg} \cdot \text{m}^{-3}$	MPa	$\text{kg} \cdot \text{m}^{-3}$	MPa	$\text{kg} \cdot \text{m}^{-3}$
49.97	928.2	49.97	915.3	49.99	902.8	50.00	890.4	49.98	878.4	49.98	866.4	49.99	854.7	49.97	843.3	50.01	831.8	49.98	820.6	49.98	809.7
39.99	923.8	39.99	910.7	39.99	897.8	39.99	885.1	40.00	872.7	39.99	860.4	40.00	848.3	40.00	836.5	40.00	824.5	39.99	812.8	39.99	801.5
29.99	919.3	30.00	905.8	30.00	892.5	29.98	879.5	29.99	866.7	29.99	854.0	29.99	841.4	29.99	829.1	29.99	816.6	30.00	804.3	29.99	792.4
20.00	914.6	19.99	900.7	20.00	887.0	19.99	873.5	19.99	860.3	19.99	847.0	20.00	834.0	19.99	821.0	19.99	807.9	19.99	794.9	19.99	782.2
10.00	909.6	9.99	895.2	9.99	881.1	9.99	867.1	9.99	853.4	10.00	839.5	9.99	825.8	9.99	812.1	9.99	798.1	10.00	784.3	9.99	770.6
5.00	907.0	5.00	892.4	4.99	878.0	4.99	863.8	5.00	849.7	5.00	835.5	4.99	821.3	4.99	807.2	5.00	792.7	4.99	778.3	4.99	764.0
3.99	906.5	3.99	891.8	3.99	877.4	3.99	863.1	3.99	848.9	4.00	834.6	3.99	820.4	3.99	806.2	3.99	791.6	4.00	777.1	3.99	762.6
3.00	905.9	2.99	891.2	2.99	876.7	2.99	862.4	2.99	848.2	2.99	833.8	3.00	819.5	2.99	805.1	2.99	790.5	2.99	775.8	3.00	761.2
1.99	905.4	1.99	890.6	1.99	876.1	1.99	861.6	1.99	847.4	1.99	832.9	1.99	818.5	2.00	804.1	1.99	789.3	2.00	774.5	1.99	759.7
0.99	904.9	0.99	890.0	1.00	875.4	0.99	860.9	1.00	846.6	0.99	832.1	0.99	817.6	1.00	803.0	1.00	788.1	0.99	773.2	0.99	758.3
0.49	904.6	0.50	889.7	0.50	875.1	0.49	860.6	0.50	846.2	0.49	831.6	0.49	817.1	0.49	802.5	0.49	787.5	0.49	772.5	0.50	757.5
0.083	904.4	0.083	889.5	0.083	874.8	0.083	860.3	0.083	845.9	0.083	831.3	0.083	816.7	0.083	802.0	0.083	787.0	0.083	771.9	0.083	756.9

^a Values extrapolated to 0.083 MPa are indicated in *italics*.

Table 2. Compressed-Liquid Densities of Methyl Oleate Measured in the High-Pressure Vibrating-Tube Densimeter along Isotherms from (270 to 470) K^a

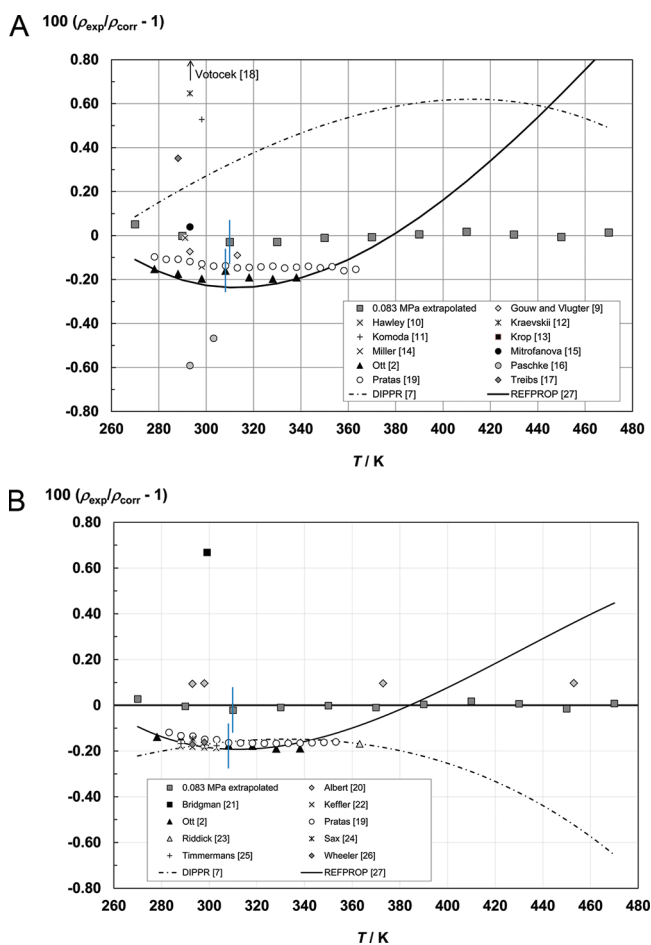
270 K			290 K			310 K			330 K			350 K			370 K			390 K			410 K			430 K			450 K			470 K		
pressure	density		pressure	density		pressure	density		pressure	density		pressure	density		pressure	density		pressure	density		pressure	density		pressure	density		pressure	density				
<i>p</i>	ρ	MPa	<i>p</i>	ρ	MPa	<i>p</i>	ρ	MPa	<i>p</i>	ρ	MPa	<i>p</i>	ρ	MPa	<i>p</i>	ρ	MPa	<i>p</i>	ρ	MPa	<i>p</i>	ρ	MPa	<i>p</i>	ρ	MPa	<i>p</i>	ρ	MPa			
	kg·m ⁻³			kg·m ⁻³			kg·m ⁻³			kg·m ⁻³			kg·m ⁻³			kg·m ⁻³			kg·m ⁻³			kg·m ⁻³			kg·m ⁻³			kg·m ⁻³				
49.83	915.9	49.96	903.4	49.99	891.1	49.99	878.9	49.98	867.0	49.97	855.1	49.99	843.6	50.00	832.2	49.99	820.8	50.01	809.7	49.97	798.8											
39.99	911.7	39.99	898.7	39.99	886.1	39.99	873.6	40.00	861.3	39.99	849.1	40.00	837.2	39.99	825.3	39.99	813.5	39.99	801.9	39.99	790.6											
29.99	907.1	29.99	893.8	29.99	880.8	29.99	868.0	30.00	855.3	29.99	842.6	29.98	830.2	30.00	817.9	29.99	805.5	29.99	793.3	29.99	781.5											
19.99	902.4	19.99	888.7	20.00	875.3	19.99	862.0	20.00	848.8	20.01	835.7	19.99	822.7	20.00	809.8	19.99	796.7	20.00	783.9	19.99	771.2											
9.99	897.4	10.00	883.3	9.99	869.3	10.00	855.6	9.99	841.8	10.00	828.1	10.00	814.5	10.00	800.8	9.99	786.9	10.00	773.1	10.00	759.5											
4.99	894.8	4.99	880.4	5.00	866.2	4.99	852.2	5.00	838.1	5.01	824.0	5.00	810.0	5.00	795.8	4.99	781.5	5.00	767.1	5.01	752.9											
3.99	894.3	3.99	879.8	4.00	865.6	3.99	851.5	3.99	837.3	3.99	823.2	3.99	809.0	3.99	794.8	3.99	780.3	3.99	765.8	3.99	751.5											
2.99	893.7	3.00	879.2	3.00	865.0	3.00	850.8	2.99	836.6	2.99	822.3	3.00	808.1	3.00	793.7	3.00	779.2	2.99	764.5	2.99	750.0											
1.99	893.2	2.00	878.6	2.00	864.3	2.00	850.1	2.00	835.8	1.99	821.4	2.00	807.1	2.00	792.7	1.99	778.0	1.99	763.2	2.00	748.6											
0.99	892.6	1.00	878.0	0.99	863.6	1.00	849.3	0.99	835.0	0.99	820.6	0.99	806.2	0.99	791.6	1.00	776.8	1.00	761.9	0.99	747.0											
0.49	892.3	0.49	877.7	0.49	863.3	0.50	849.0	0.50	834.6	0.50	820.1	0.49	805.7	0.49	791.0	0.50	776.2	0.49	761.2	0.49	746.3											
0.083	892.1	0.083	877.5	0.083	863.0	0.083	848.7	0.083	834.3	0.083	819.7	0.083	805.2	0.083	790.6	0.083	775.7	0.083	760.6	0.083	745.7											

Values extrapolated to 0.083 MPa are indicated in *italics*.

^a Values extrapolated to 0.083 MPa are indicated in *italics*.

Table 3. Parameters of the Correlation (eq 1), for the Densities Methyl Linoleate and Methyl Oleate at Ambient Pressure of 0.083 MPa and Temperatures from (270 to 470) K

parameter	methyl linoleate		methyl oleate	
	value	standard deviation	value	standard deviation
$\beta_1/\text{kg}\cdot\text{m}^{-3}$	174.41	0.05	170.56	0.05
β_2	0.39868	0.00004	0.39673	0.00004
β_3/K	767.40	0.03	764.00	0.03
β_4	0.54592	0.00007	0.54249	0.00007

Figure 1. Deviations of the extrapolated density data of the methyl linoleate of this work and literature data from the correlation (eq 1). Also shown are deviations of the DIPPR⁷ and REFPROP²⁷ correlations.

the density values by up to $0.3 \text{ kg}\cdot\text{m}^{-3}$. If the reported densities were reduced to reflect this bias, agreement with the majority of the literature data would be even better.

In Figure 1a the DIPPR⁷ correlation was derived from all of the data sources shown with the exceptions of Ott et al.,² Paschke et al.,¹⁶ and Pratas et al.¹⁹ In the temperature range from (270 to 370) K the DIPPR⁷ correlation shows positive deviations from our correlation, while the deviations of the REFPROP²⁷ correlation (which included the data of Ott et al.²) are negative and agree closely with the data of Pratas et al.¹⁹ Much of the data included in the DIPPR⁷ correlation have values larger than those

Table 4. Parameters of the Correlation (eqs 2 and 3), for the Compressed-Liquid Densities of Methyl Linoleate and Methyl Oleate at Temperatures from (270 to 470) K and Pressures up to 50 MPa

parameter	methyl linoleate		methyl oleate	
	value	standard deviation	value	standard deviation
C	0.08133	0.00009	0.08181	0.00009
D ₁	377.6	0.5	379.7	0.5
D ₂	−316.4	0.5	−323.1	0.5
D ₃	70.01	0.16	72.95	0.16

of Ott et al.,² Paschke et al.,¹⁶ and Pratas et al.¹⁹ The deviation of the single data point of Votocek et al.¹⁸ (1.07 %) being so much greater that it is not shown in the figure. The DIPPR⁷ and the REFPROP²⁷ correlations being based on somewhat conflicting data sets thus predict considerably different values for density in the temperature range (278 to 363) K. The larger deviations of both the REFPROP²⁷ and DIPPR⁷ correlations from our data at temperatures above 340 K are expected, as prior to this report, there were no available data to constrain the fits.

The DIPPR⁷ correlation in Figure 1b shows a negative deviation from our correlation below approximately 370 K, as does the REFPROP²⁷ correlation, and there is good agreement between the two database correlations in this temperature range. Our extrapolated densities for methyl oleate are higher in comparison to the majority of the ambient pressure data in the literature, but as mentioned above, are within the combined uncertainty bounds of our data (± 0.1 %) and the data of Ott et al.² (± 0.1 %) which agrees well with much of the literature data.

The compressed-liquid density data were correlated with a Tait equation similar to that of Dymond and Malhotra²⁸ of the form

$$\rho(T, p) = \frac{\rho_{\text{ref}}(T, p_{\text{ref}})}{1 - C \ln \left(\frac{p + D(T)}{p_{\text{ref}} + D(T)} \right)} \quad (2)$$

where $\rho_{\text{ref}}(T)$ is the temperature-dependent density at the reference pressure $p_{\text{ref}} = 0.083$ MPa from eq 1. The temperature dependence of the parameter C was omitted because it was not needed to fit the data within their experimental uncertainty. The temperature dependence of the Tait parameter $D(T)$ was expressed by a quadratic polynomial,

$$D(T) = D_1 + D_2 T_r + D_3 T_r^2 \quad (3)$$

where T_r is the absolute temperature T divided by 273.15 K. Parameters for eqs 2 and 3 are given in Table 4. Figure 2a,b shows deviations of the measured compressed-liquid density data relative to the adjusted Tait equation of state. These correlations represent both our methyl linoleate and methyl oleate compressed-liquid density data well within their estimated uncertainty of 0.1 %. One advantage of the Tait equation of state is that it can be reliably extrapolated to pressures considerably higher than those to which it was adjusted.²⁹ In the case of the samples measured in this work, we expect that extrapolations to pressures of 100 MPa will yield densities within the estimated experimental uncertainty of 0.1 %.

A search of the literature revealed no compressed-liquid density data for methyl linoleate, and only two sets of data for methyl oleate: Bridgman²¹ and Pratas et al.³⁰ The Bridgman²¹

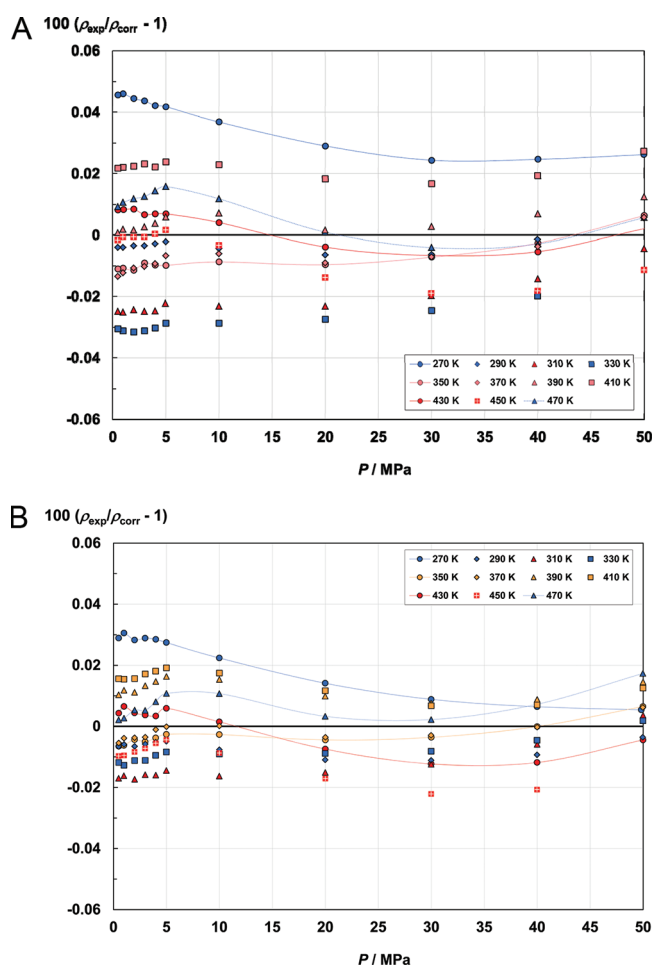


Figure 2. Deviations of density data of compressed-liquid methyl linoleate from the correlation (eqs 2 and 3), as a function of pressure.

data, however, are from 1932, and the sample purity may be questionable. There is no statement of purity in the paper, only that the sample “was obtained from Eastman Kodak Co. and used without further purification.” The single ambient pressure value from this reference had by far the largest deviation from our correlation (eq 1) of any of the literature data and as such was not in agreement with the majority of the data. Additionally, all but 2 of the 22 compressed-liquid data points of Bridgman²¹ were taken at pressures above 50 MPa, and 17 of them were taken at pressures greater than 100 MPa (the highest pressure at which we would expect our correlation to extrapolate within the experimental uncertainty of 0.1 %). For the above reasons, no comparison of our data to the Bridgman²¹ data is provided.

Figure 3 shows deviations of our measured compressed-liquid density data for methyl oleate and that of Pratas et al.³⁰ to values predicted by REFPROP²⁷ as a function of temperature. The Pratas et al.³⁰ data range was in temperature from (293 to 333) K and in pressure from (0.1 to 45) MPa. The agreement between the data reported in this work and that of Pratas et al.³⁰ is relatively good, but not within the combined uncertainties of the two data sets as our uncertainty is 0.1 % and that of Pratas et al.³⁰ is 0.1 kg·m^{−3} or approximately 0.01 %. The large deviations of our data from that of the REFPROP²⁷ predictions at higher temperatures are probably due in large part to the fact that the REFPROP²⁷ correlation

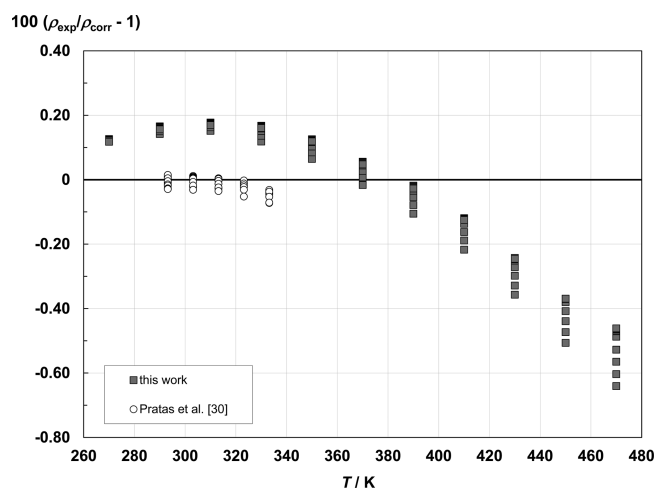


Figure 3. Deviations of density data of compressed-liquid methyl oleate from the REFPROP²⁷ database as a function of temperature.

was formulated without any compressed-liquid density data and no density data above 338 K.

5. CONCLUSIONS

Densities of compressed-liquid methyl linoleate and methyl oleate samples have been measured over a temperature range of (270 to 470) K with pressures to 50 MPa. Densities of the compressed-liquids measured in this work were extrapolated to ambient pressure for comparison with existing literature data and show good agreement. The reported compressed-liquid densities for methyl linoleate provide data in a temperature and pressure range not otherwise available in the literature and those for methyl oleate extend the available data from (333 to 470) K. Correlations formulated for the reported compressed-liquid densities represent the data well within their experimental uncertainty of 0.1 % and provide a predictive tool for engineering applications.

AUTHOR INFORMATION

Corresponding Author

*Phone: 1-303-497-5786. Fax: 1-303-497-5224. E-mail: outcalt@boulder.nist.gov.

REFERENCES

- (1) *Biodiesel Handling and Use Guide*, 4th ed.; NREL/TP-540-43672, 56; N.R.E. Laboratory, U.S. Department of Commerce, National Technical Information Service: Springfield, VA, 2009; <http://www.nrel.gov/vehiclesandfuels/pdfs/43672.pdf>.
- (2) Ott, L. S.; Huber, M. L.; Bruno, T. J. Density and Speed of Sound Measurements on Five Fatty Acid Methyl Esters at 83 kPa and Temperatures from (278.15 to 338.15) K. *J. Chem. Eng. Data* **2008**, *53*, 2412–2416.
- (3) Huber, M. L.; Lemmon, E. W.; Kazakov, A.; Ou, L. S.; Bruno, T. J. Model for the Thermodynamic Properties of a Biodiesel Fuel. *Energy Fuels* **2009**, *23*, 3790–3797.
- (4) Smith, B. L.; Ott, L. S.; Bruno, T. J. Composition-Explicit Distillation Curves of Commercial Biodiesel Fuels: Comparison of Petroleum-Derived Fuel with B20 and B100. *Ind. Eng. Chem.* **2008**, *47*, 5832–5840.
- (5) Bruno, T. J.; Svoronos, P. D. N. *CRC Handbook of Basic Tables for Chemical Analysis*; CRC Taylor and Francis: Boca Raton, FL, 2011.
- (6) Outcalt, S. L.; McLinden, M. O. Automated Densimeter for the Rapid Characterization of Industrial Fluids. *Ind. Eng. Chem. Res.* **2007**, *46*, 8264–8269.
- (7) Rowley, R. L.; Wilding, W. V.; Oscarson, J. L. *DIPPR Project 801 Data Compilation of Pure Compound Properties*; AIChE: New York, 2007; <http://DIPPR.BYU.Edu>.
- (8) *Estimation of Critical Properties of Organic Compounds*; University of Wisconsin College of Engineering: Madison, WI, April 1955.
- (9) Gouw, T. H.; Vlugter, J. C. Physical Properties of Fatty Acid Methyl Esters. I. Density and Molar Volume. *J. Am. Oil Chem. Soc.* **1964**, *41*, 142–145.
- (10) Hawley, G. G.; Lewis, R. J. S. *The Condensed Chemical Dictionary*, 14th ed.; Wiley: New York, 2001.
- (11) Komoda, M.; Harada, I. Interaction of Tocored With Unsaturated Fatty Esters. *J. Am. Oil Chem. Soc.* **1970**, *47*, 249–253.
- (12) Kraevskii, A. A.; Pyatnova, Y. B.; Myakova, G. I.; Sarycheva, I. K.; Predorazhenskii, N. A. The Total Synthesis of Linoleic, Linolenic, Arachidonic, and 7,10,13,16-Docosatetraenoic Acids. *Trans. Dokl. Akad. Nauk. SSSR* **1962**, *146*, 1349–1351.
- (13) Krop, H. B.; Velzen, M. J. M.; Parsons, J. R.; Govers, H. A. J. Determination of Environmentally Relevant Physical-Chemical Properties of Some Fatty Acid Esters. *J. Am. Oil Chem. Soc.* **1997**, *74*, 309–315.
- (14) Miller, N. F. The Wetting of Steel Surfaces by Esters of Unsaturated Fatty Acids. *J. Phys. Chem.* **1946**, *50*, 300–319.
- (15) Mitrofanova, T. K.; Gusev, V. D.; Preobrazhenskii, N. A. Investigations in the Field of Lipids XL. Synthesis of the glyceride principles of sunflower-seed oil. *J. Org. Chem. USSR* **1966**, *2*, 1748–1750.
- (16) Paschke, R. F.; Jackson, J. E.; Wheeler, D. H. Thermal Polymerization of Drying Oils: Isomers of Methyl Linoleate. *Ind. Eng. Chem.* **1952**, *44*, 1113–1118.
- (17) Treibs, W. Zur Autoxydation sauerstoffaktiver Sauren. IV. Mittel: Über die refraktometrische Analyse der Sauerstoff-anlagerung an die Methylester. *Chem. Ber.* **1942**, *75*, 925–933.
- (18) Votocek, E.; Valentin, F.; Bulir, J. Sur les principes immediats de l'huile des graines de molene (verbascum). *Collect. Czech. Chem. Commun.* **1936**, *8*, 455–460.
- (19) Pratas, M. J.; Freitas, S.; Oliveira, M. B.; Monteiro, S. C.; Lima, A. S.; Coutinho, J. A. P. Densities and Viscosities of Fatty Acid Methyl and Ethyl Esters. *J. Chem. Eng. Data* **2010**, *55*, 3983–3990.
- (20) Albert, O. Viscosity measurements on homologous ester series with special regard to the relations of thorpe and roger. *Z. Phys. Chem., Abt. A* **1938**, *182*, 421.
- (21) Bridgman, P. W. Volume-Temperature-Pressure Relations for Several Non-Volatile Liquids. *Proc. Am. Acad. Arts Sci.* **1932**, *67*, 1–27.
- (22) Keffler, L.; MacLean, J. H. Homology in long-chain compounds. I. Oleic acid and the n-alkyl oleates. *J. Soc. Chem. Ind., London, Trans. Commun.* **1935**, *54*, 178.
- (23) Riddick, J. A.; Bunger, W. B.; Sakano, T. K., *Organic Solvents: Physical Properties and Methods of Purification*, 3rd ed.; Wiley Interscience: New York, 1970.
- (24) Sax, N. I. *Dangerous Properties of Industrial Materials*, 6th ed.; Van Nostrand Reinhold Company: New York, 1984.
- (25) Timmermans, J. *Physico-Chemical Constants of Pure Organic Substances*, Vol. II; Elsevier: New York, 1965.
- (26) Wheeler, D. H.; Riemenschneider, R. W. The Preparation and Properties of Highly Purified Methyl Oleate. *Oil Soap* **1939**, *16*, 207–209.
- (27) Lemmon, E. W.; Huber, M. L.; McLinden, M. O. *NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP*, Version 9.0; NIST: Gaithersburg, MD, 2010. <http://www.nist.gov/srd/nist23.htm>.
- (28) Dymond, J. H.; Malhotra, R. The Tait equation: 100 years on. *Int. J. Thermophys.* **1988**, *9*, 941–951.
- (29) Laesecke, A.; Outcalt, S. L.; Brumback, K. J. Density and Speed of Sound Measurements of Methyl- and Propylcyclohexane. *Energy Fuels* **2008**, *22*, 2629–2636.
- (30) Pratas, M. J.; Oliveira, M. B.; Pastoriza-Gallego, M. J.; Queimada, A. J.; Pieiro, M. M.; Coutinho, J. A. P. High-Pressure Biodiesel Density: Experimental Measurements, Correlation, and Cubic-Plus-Association Equation of State (CPA EoS) Modeling. *Energy Fuels* **2011**, *25*, 3806–3814.