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Comparison of Jet Fuels by Measurements of Density and Speed of Sound of a Flightline JP-8[†]

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The density of a flightline jet fuel (JP-8) was measured with two vibrating-tube densimeters. The combined range of the data is from 270 to 470 K with pressures of 40 MPa. The speed of sound in the fuel was measured with a propagation time method at ambient pressure from 278.15 to 343.15 K. The density and speed of sound results at ambient pressure were combined to obtain the adiabatic compressibility. A correlation is reported that represents the temperature and pressure dependence of the experimental data within their estimated uncertainties and can be extrapolated meaningfully beyond the pressure range of the data. The data from this jet fuel are compared to those of four previously measured jet fuels to examine the differences in their densities and speeds of sound.

1. Introduction

Energy independence through a secure and diverse supply of fuel is of paramount strategic importance. Technologies to use the vast domestic coal reserves in the U.S. are being advanced in response to the growing competition between developing nations for oil resources.[1] Unlike automotive transportation fuels, which can be specific in countries or regions, the global nature of the aviation industry requires a fuel that is uniform worldwide in supply security and performance. Adding to these requirements are environmental concerns over the sustainability of aviation, resulting in driving forces to diversify the fuel supply away from crude oil to alternative feed stocks, including biomass.[2] These pressures have led to the development of synthetic fluids, such as S-8 (CAS No. 437986-20-4), produced from natural gas by the Fischer–Tropsch process, as well as coal-derived fluids that could potentially serve as generic fuels or components of such fuels. The baseline fuel is kerosene-JP-8 + 100 (military) or Jet A (civil) according to the standards MIL-DTL-83133F and American Society for Testing and Materials (ASTM) D7566.[3,4] The measurements reported here are part of a project to characterize fuels and rocket propellants,[5−11] to develop a knowledge base for their formulation and optimization.

Table 1. Density, Speed of Sound, and Adiabatic Compressibility of JP-8 3773 Measured in the Density and Sound Speed Analyzer[a]

	JP-8 3773		
temperature, T (K)	density, ρ (kg m^{-3})	speed of sound, w (m s^{-1})	adiabatic compressibility, κ_s (T Pa^{-1})
278.15	806.8	1366.0	664.2
283.15	802.9	1345.9	687.5
293.15	795.1	1306.3	737.1
303.15	787.4	1267.5	790.6
313.15	779.8	1229.3	848.7
323.15	772.2	1191.8	911.7
333.15	764.7	1154.9	980.5
343.15	757.1	1118.8	1055

[a] The ambient pressure during the measurements was 0.083 MPa.

The major chemical constituents of JP-8 are nearly identical to those of Jet A, the most common commercial aviation turbine fuel in the United States of America. In this work, a sample of JP-8 was taken directly from the flightline of Wright-Patterson Air Force Base (AFB) and studied by measurements of density and speed of sound. Density is an important fuel property directly related to aircraft range. Some fuel-gauging systems give readings proportional to the

[†]Disclaimer: To describe materials and experimental procedures adequately, it is occasionally necessary to identify commercial products by the names or labels of manufacturers. 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.

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Table 2. Compressed-Liquid Densities of JP-8 3773 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	
pressure, p (MPa)	density, ρ (kg m^{-3})	pressure, p (MPa)	density, ρ (kg m^{-3})	pressure, p (MPa)	density, ρ (kg m^{-3})	pressure, p (MPa)	density, ρ (kg m^{-3})	pressure, p (MPa)	density, ρ (kg m^{-3})	pressure, p (MPa)	density, ρ (kg m^{-3})
39.99	833.2	39.97	821.0	39.99	808.7	40.00	796.0	40.00	783.9	40.00	771.8
35.00	830.8	35.00	818.3	35.00	805.7	35.00	792.9	35.00	780.5	35.00	768.2
30.00	828.2	30.00	815.6	29.99	802.7	29.99	789.6	30.00	777.0	30.00	764.4
24.99	825.6	24.98	812.7	25.00	799.5	24.99	786.2	25.00	773.3	24.99	760.4
20.00	823.0	20.00	809.8	20.00	796.2	19.99	782.7	19.99	769.5	19.99	756.2
15.00	820.2	15.00	806.8	14.99	792.8	14.98	779.0	15.00	765.5	14.99	751.7
10.00	817.4	9.99	803.7	10.00	789.3	10.00	775.2	9.99	761.2	10.01	747.0
4.99	814.4	5.00	800.4	4.99	785.7	5.01	771.1	5.00	756.7	4.99	742.0
3.99	813.8	3.99	799.7	4.00	784.9	4.00	770.3	3.99	755.8	3.99	740.9
3.00	813.2	3.00	799.0	3.00	784.2	2.99	769.4	2.99	754.8	2.99	739.9
1.99	812.6	1.99	798.4	1.99	783.4	1.99	768.6	2.00	753.9	1.99	738.8
1.01	812.0	1.00	797.7	1.00	782.6	1.00	767.7	1.01	752.9	0.99	737.7
0.50	811.6	0.49	797.3	0.50	782.2	0.49	767.2	0.50	752.4	0.49	737.1
0.083	*811.4*	*0.083*	*797.0*	*0.083*	*781.9*	*0.083*	*766.9*	*0.083*	*752.0*	*0.083*	*736.6*

390 K		410 K		430 K		450 K		470 K	
pressure, p (MPa)	density, ρ (kg m^{-3})	pressure, p (MPa)	density, ρ (kg m^{-3})	pressure, p (MPa)	density, ρ (kg m^{-3})	pressure, p (MPa)	density, ρ (kg m^{-3})	pressure, p (MPa)	density, ρ (kg m^{-3})
39.99	759.9	39.99	747.9	39.98	736.0	40.02	724.2	40.01	712.5
35.00	755.9	35.00	743.7	34.99	731.4	34.99	719.2	34.99	707.2
29.99	751.8	29.98	739.2	29.99	726.6	29.99	714.0	29.99	701.5
25.00	747.5	25.01	734.5	25.00	721.4	24.99	708.4	24.99	695.4
20.00	742.9	20.00	729.5	19.99	715.9	19.99	702.3	20.01	688.7
14.99	738.0	14.99	724.1	15.00	709.9	15.00	695.7	15.00	681.4
10.00	732.6	10.00	718.2	10.00	703.4	10.00	688.4	9.99	673.3
4.99	727.0	4.99	711.9	5.00	696.2	5.00	680.3	4.99	664.0
4.00	725.8	3.99	710.5	4.00	694.7	4.00	678.5	4.00	661.9
3.00	724.6	2.99	709.1	2.99	693.1	3.00	676.7	2.99	659.8
2.00	723.4	1.99	707.7	2.00	691.5	1.99	674.8	1.99	657.6
1.00	722.1	0.99	706.3	0.99	689.9	0.99	672.9	0.99	655.3
0.49	721.5	0.49	705.5	0.49	689.0	0.49	671.9	0.49	654.2
0.083	*721.0*	*0.083*	*704.9*	*0.083*	*688.3*	*0.083*	*671.1*	*0.083*	*653.2*

[a] Values extrapolated to 0.083 MPa are indicated in italics.

speed of sound; therefore, this property is also an important fuel parameter. The speed of sound in a material characterizes its susceptibility to pressure changes at constant entropy. Therefore, while density is a static property, the speed of sound provides information about effects relating to the distribution of energy on a molecular scale.[12] Consequently, these two properties reflect the effects of fuel composition from two different angles. Together, these properties can be used to develop Helmholtz formulations for thermodynamic equilibrium properties, which provide a framework to predict those fluid properties that have not yet been measured. In this work, the density of the flightline JP-8 fuel has been measured in the temperature range from 270 to 470 K with pressures of 40 MPa. The speed of sound was measured at ambient pressure from 278.15 to 343.15 K. Compressed-liquid density data have been extrapolated to the local ambient pressure of 0.083 MPa and combined with our measured density data at ambient pressure for a wide-ranging correlation that covers the entire measurement range. The measured properties of JP-8 are put in context of the properties of four Jet A fuels that we have measured previously.[13] As alternative aviation fuels are evaluated, density-versus-temperature and speed of sound-versus-temperature behavior are compared to the existing fuel "experience base" to ensure that the alternatives will be "drop-in" replacements.

2. Sample Liquid

The sample measured in this work was provided by the Fuels Branch of the Air Force Research Laboratory, Wright-Patterson AFB, Dayton, OH, and was designated POSF-3773. The designation is only for identification and does not describe the fuel composition. Hereafter, the sample is referred to as JP-8 3773. The compositions and distillation curves of this sample and the synthetic S-8 were measured and analyzed in detail by Smith and Bruno.[14] They found that the composition of JP-8 3773 was similar to other Jet A fuels that have been investigated previously,[13] but the flightline fuel also contained a full additive package with an icing inhibitor, a corrosion inhibitor, a lubricity enhancer, and an anti-static additive.

3. Experimental Section

Two apparatuses were used to perform the density measurements presented here. Both instruments employ vibrating-tube sensors, but they have different precisions. Their calibration and operating procedures have been described previously in the context of measurements of methyl- and propylcyclohexane.[15]

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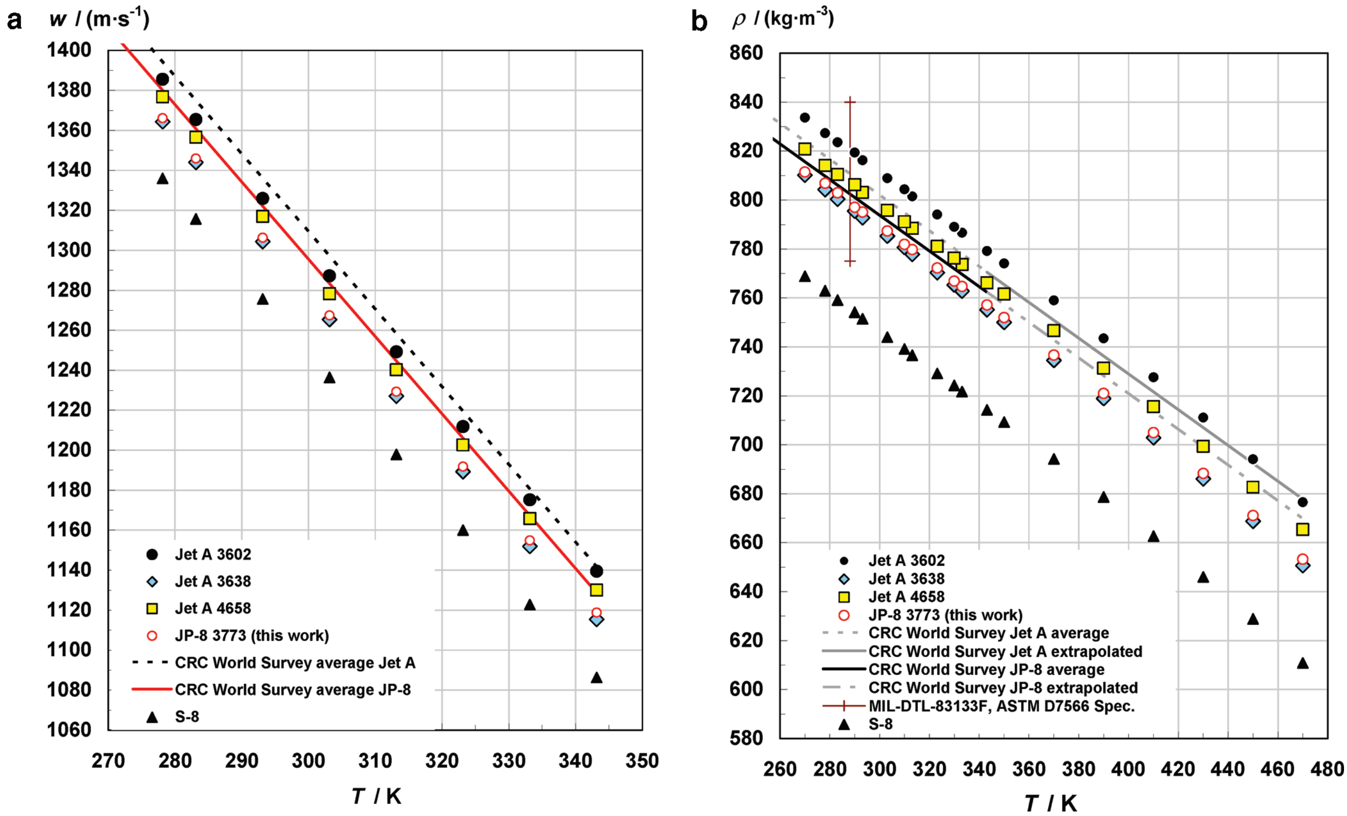

Figure 1. (a) Measured speed of sound data and (b) measured and extrapolated density data of JP-8 3773 compared to three other Jet A fuels reported previously in ref 13 and the correlations for the speed of sound and density, respectively, of average Jet A and JP-8 from the CRC World Survey[19] as a function of the temperature at ambient pressure.

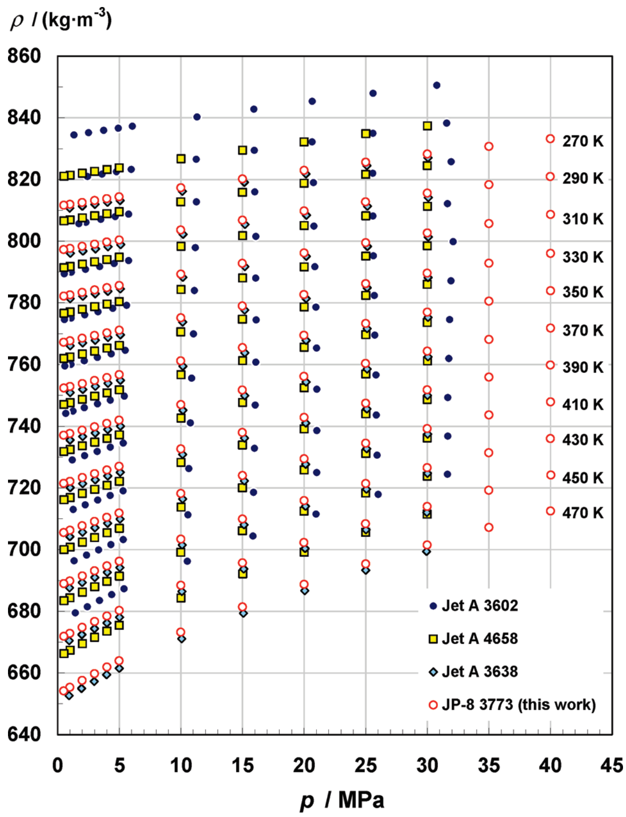

Figure 2. Comparison of the compressed-liquid density data of JP-8 3773 and three other Jet A fuels reported previously in ref 13.

Table 3. Parameters of the Correlation (eq 2) for the Speed of Sound of the JP-8 3773 at Ambient Pressure of 0.083 MPa and Temperatures from 278.15 to 343.15 K[a]

parameter	JP-8 3773 value	JP-8 3773 standard deviation
A_1 (m s^{-1})	2754.1	3.2
A_2 (m s^{-1} K^{-1})	−5.953	0.02
A_3 (m s^{-1} K^{-2})	3.46×10^{-3}	3.3×10^{-5}
AAD (%)		0.029
rmsd (%)		0.023

[a] Average absolute deviations (AADs) and root mean square deviations (rmsd's) are given to indicate the quality of the correlations.

Table 4. Parameters of the Correlation (eq 3) for the Density of JP-8 3773 at Ambient Pressure of 0.083 MPa and Temperatures from 270 to 470 K

parameter	JP-8 3773 value	JP-8 3773 standard deviation
β_1 (kg m^{-3})	277.969	0.027
β_2	0.525 720	2.5×10^{-5}
β_3 (K)	564.767	0.016
β_4	0.622 487	3.9×10^{-5}

A density and sound speed analyzer (DSA 5000, Anton Paar Corp.) was used to determine these properties at ambient atmospheric pressure (on average 0.083 MPa at the elevation of 1633 m of Boulder, CO). Temperature scans were programmed in the units of the instrument from 70 to 10 °C, in decrements of 10 °C, followed by a single measurement at 5 °C. The stated uncertainty in temperature by the manufacturer is 0.01 °C. The instrument was calibrated with air and deionized water at 20 °C.

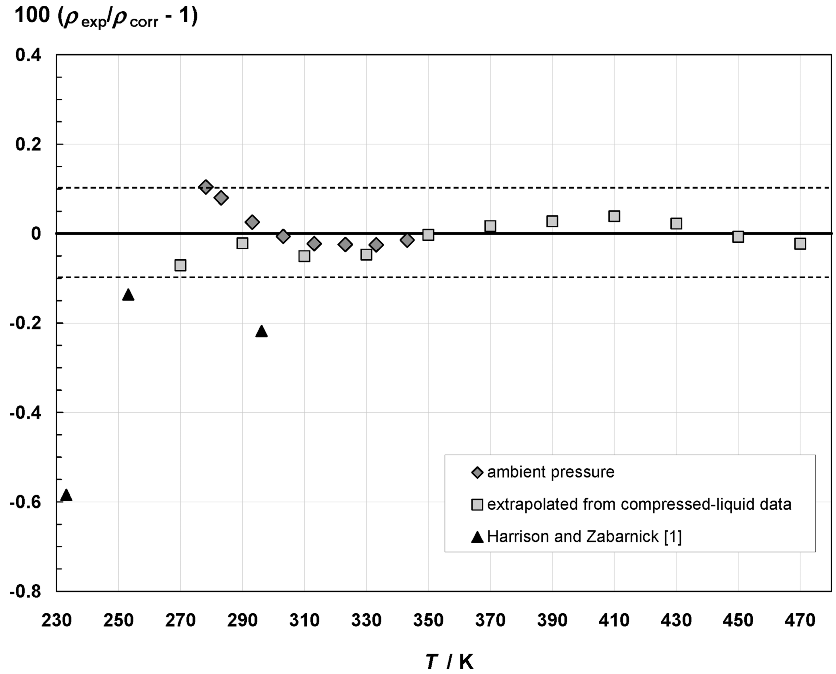

Figure 3. Deviations of measured and extrapolated ambient pressure density data of JP-8 3773 from the correlation (eq 3). Also shown are deviations of the data by Harrison and Zabarnick.[1]

The reproducibility of reference values for the density and sound speed of water at 20 °C to within 0.01% was checked before and after measurements of the fuel samples to ensure that one sample had been removed completely before another sample was injected. The density and the speed of sound were measured on the same aliquot of the test liquid JP-8 3773 that remained in the instrument during an entire temperature scan. The relative standard deviation of the repeated density measurements was lower than 0.002%, and the quoted uncertainty by the manufacturer is 0.1% for both the density and speed of sound determination. However, in our most recent measurements, we obtained conservative estimates for the expanded uncertainty of the speed of sound determinations of 0.3% (coverage factor $k = 2.3$) and 0.04% ($k = 2.3$) for the density determinations.[8] Compressed-liquid density measurements were made with the fully automated densimeter of Outcalt and McLinden[16] over the temperature range of 270−470 K and up to pressures of 40 MPa. Uncertainty in temperature and pressure are 0.03 K ($k = 1$) and 5 kPa ($k = 1$), respectively. The densimeter was calibrated with propane[17] and toluene,[18] and the expanded uncertainty in density is calculated to be 0.81 kg m^{-3} ($k = 2$).

4. Results

Table 1 lists values of density, speed of sound, and derived adiabatic compressibilities for the JP-8 3773 sample at the local atmospheric pressure of 0.083 MPa from 278.15 to 343.15 K. Adiabatic compressibilities were calculated from the measured densities and speeds of sound according to the thermodynamic relation

$$\kappa_s = -(\partial V/\partial p)_s/V = 1/(\rho w^2) \qquad (1)$$

where V denotes volume, p is the pressure, ρ is the density, and w is the speed of sound. The subscript s indicates "at constant entropy".

Table 2 lists measured density values of compressed-liquid JP-8 3773 from 270 to 470 K with pressures of 40 MPa. It includes 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. This extrapolation was performed to examine the consistency of the compressed-liquid data with the measurement results at ambient pressure from the density and sound speed analyzer. This consistency will be addressed in the Correlation of Data section below.

The temperature dependencies of the data for speed of sound and density at ambient pressure are illustrated in panels a and b of Figure 1, respectively. Variations in sample composition can be deduced from these graphs because the data for JP-8 3773 reported in this work are put into context with those of four other jet fuels previously measured: Jet A 3602, Jet A 3638, Jet A 4658, and the synthetic fuel S-8. Included in both diagrams are the respective correlations for Jet A and JP-8 properties from the Coordinating Research Council (CRC) World Survey.[19] Figure 1a shows that S-8 has the lowest speed of sound of all of the fuels considered here, while the correlation for average Jet A from the CRC World Survey gives values that exceed those of the fuels presented in this work. The correlation for the speed of sound for average JP-8 from the CRC World Survey is on average 14 m s^{-1} lower than that for Jet A. The speed of sound of JP-8 3773 is yet lower than this correlation and close to that of Jet A 3638, with a slightly lower temperature dependence. The density diagram in Figure 1b covers the extended temperature range from 270 to 470 K and includes the data measured in the density and sound speed analyzer combined with the densities extrapolated to 0.083 MPa from the compressed-liquid

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Table 5. Parameters of the Correlation (eq 4) for the Density of JP-8 3773 in Terms of Temperature and Pressure

	JP-8 3773	
parameter	value	standard deviation
C	81.95059×10^{-3}	2.0×10^{-4}
D_1	361.3	1.2
D_2	−339.2	1.4
D_3	82.8	0.43

measurements. It also includes the specification range of density from 775 to 840 kg m^{-3} that is required for aviation turbine fuels at 288.15 K (15 °C) according to the standards MIL-DTL-83133F and ASTM D7566.[3,4] All fuels in the comparison meet this requirement, with the exception of S-8, the density of which at 288.15 K (15 °C) is obtained from the correlation of our experimental data as 755.14 kg m^{-3}, while the lower specification margin is 775 kg m^{-3}.[3]

Similar to its speed of sound, the density of JP-8 3773 is also closest to that of Jet A 3638. The Jet A 3638 sample was known to be unusual in that it showed a remarkably high volatility and an unusually low aromatic content[5] while still meeting the specifications for Jet A. The sample designated Jet A 4658 was a composite prepared by mixing approximately equal volumes of five individual batches of Jet A to represent what might be considered a typical Jet A.[5] While its density is closest to the correlation for average Jet A of the CRC World Survey, its speed of sound is lower than that and ranges between those of JP-8 3773 and Jet A 3602.

The agreement (0.4−0.7%) between the measured densities of JP-8 3773 and the correlation for average JP-8 from the CRC World Survey is better than that between the respective values of the speed of sound (0.9−1.3%). Figure 1b also shows a comparison between the density and temperature dependencies of our measurement results and the correlations from the CRC World Survey when they are extrapolated beyond their fit range from 343.15 to 470 K. The CRC correlation is linear (a first-order polynomial in temperature) and deviates progressively from the measured densities, which decrease in a nonlinear fashion with the temperature. Consequently, the CRC World Survey correlations should not be extrapolated. In future surveys, the linear correlations could be replaced by correlations such as the Rackett-type eq 3 in the next section of this work, which does represent the progressive density decrease with the temperature.

Figure 2 illustrates primarily the pressure dependence of the measured densities of compressed-liquid JP-8 3773 in comparison to our previously published compressed-liquid densities of three Jet A samples. In the figure, the height of the symbols is representative of the uncertainty in the density measurements (± 0.81 kg m^{-3}, $k = 2$) but the width is not representative of the uncertainty in pressure (± 10 kPa, $k = 2$). It should be noted that the measurements presented here for JP-8 3773 covered a larger pressure range from 0.5 to 40 MPa than those of the Jet A fuels, where in some instances, the lowest pressure measured was 1.5 MPa and the highest pressure was approximately 30 MPa. Therefore, the density of JP-8 3773 presented in Figure 2 covers a wider range than that of Jet A fuels. Figure 2 reveals more clearly the differences in the density surfaces of Jet A 3602, Jet A 4658, Jet A 3638, and JP-8 3773. The latter two are very close across the pressure range, but deviations emerge toward higher temperatures. The density surface of Jet A 4658 is significantly offset from that of the two former ones, and the initial pressure

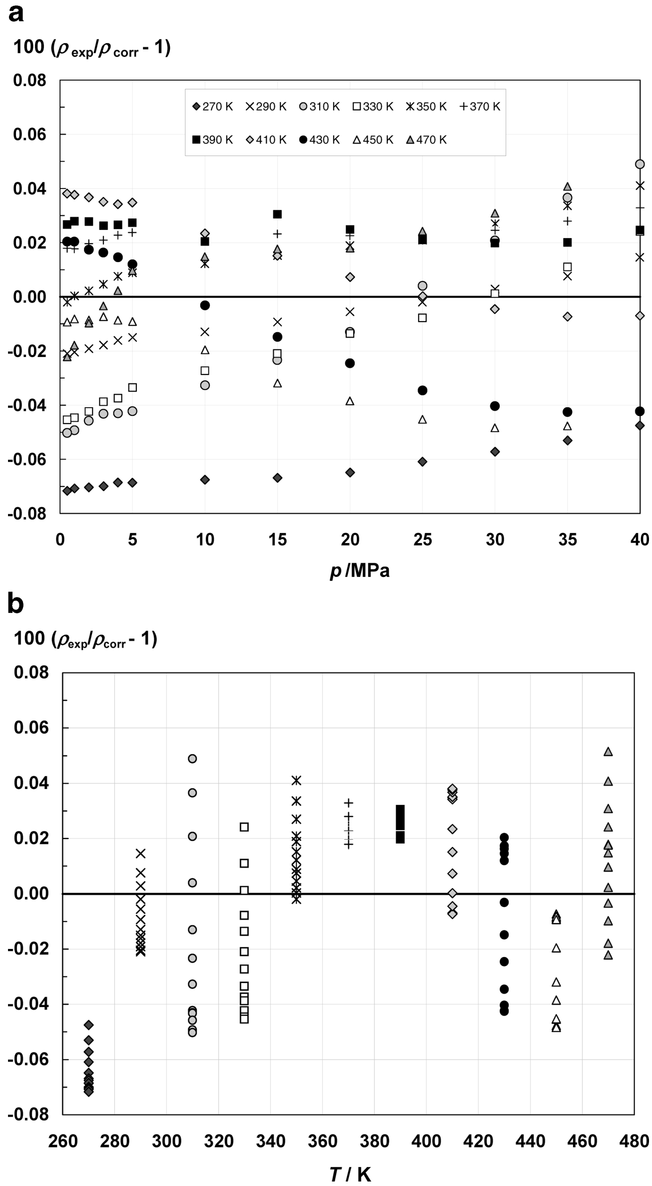

Figure 4. (a) Deviations of density data of compressed-liquid JP-8 3773 from the correlation (eq 4), as a function of the (a) pressure and (b) temperature.

dependence up to 5 MPa changes markedly with the temperature. The density offset corresponds approximately to a temperature drop of 20 K. In turn, the density surface of Jet A 3602 is offset by a similar difference from that of Jet A 4658. In the comparison of Jet A 3602 to Jet A 4658, the density difference increases with a decreasing temperature, so that the highest offset occurs at 270 K.

5. Correlation of Data

To facilitate the use of our measurement results in engineering applications, we provide the following correlations. The speed of sound data at local atmospheric pressure were correlated as a function of the temperature with the second-order polynomial.

$$w = A_1 + A_2 T + A_3 T^2 \tag{2}$$

The symbol w denotes the speed of sound in units of m s^{-1}, and T is the absolute temperature in kelvins. The values of the adjustable parameters A_1-A_3 and their standard deviations are listed in Table 3. This correlation represents the speed of sound data well within their estimated experimental uncertainty.

Density measurements at ambient pressure and values extrapolated to 0.083 MPa from experimental compressed-liquid data as reported in Table 2 were correlated jointly with a Rackett-type equation to check the repeatability of the instruments and the consistency of our data in the combined temperature range of 270−470 K. The equation is written as

$$\rho = \beta_1 \beta_2^{-\left(1+\left(1-\frac{T}{\beta_3}\right)^{\beta_4}\right)} \quad (3)$$

Table 4 lists the correlation parameters for eq 3 obtained by nonlinear least-squares regression. In Figure 3, this correlation serves as the baseline to compare the ambient pressure and extrapolated values. It can be seen that both our measured and extrapolated data agree within the bounds of the estimated uncertainty of the density measurements, shown as the dashed line. Included in the graph are the data of Harrison and Zabarnick. These data were measured with a pycnometer on a sample also designated JP-8 3773 from Wright-Patterson AFB. The data were provided to us by the authors; however, no uncertainties were assigned. Considering this and the fact that two data points of Harrison and Zabarnick are at temperatures below the fit range of the Rackett correlation of our results (eq 3), the agreement between the two series of data is good.

The compressed-liquid density data were correlated with a Tait equation similar to that of Dymond and Malhotra[20] of the form

$$\rho(T,p) = \frac{\rho_{\mathrm{ref}}(T, p_{\mathrm{ref}})}{1 - C \ln\left(\dfrac{p + D(T)}{p_{\mathrm{ref}} + D(T)}\right)} \quad (4)$$

where $\rho_{\mathrm{ref}}(T)$ is the temperature-dependent density at the reference pressure $p_{\mathrm{ref}} = 0.083$ MPa from eq 3. 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

$$D(T) = D_1 + D_2 T_{\mathrm{r}} + D_3 T_{\mathrm{r}}^2 \quad (5)$$

where T_{r} is the absolute temperature T divided by 273.15 K. Parameters for eq 4 are given in Table 5. Panels a and b of Figure 4 show deviations of the measured compressed-liquid density data relative to the adjusted Tait equation of state. This correlation represents our data with an AAD of 0.027%, which is well within their estimated uncertainty. 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.[15] In the case of JP-8 3773, we expect that extrapolations to pressures of 100 MPa will yield densities within the estimated experimental uncertainty of 0.1%.

6. Conclusions

Density and speed of sound at ambient pressure and compressed-liquid densities of a flightline JP-8 sample have been measured over a temperature range of 270−470 K with pressures of 40 MPa. The measurement results form the basis for comparisons of these properties to those of four other aviation turbine fuels that were measured previously in this laboratory.[13]

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