Density and Speed of Sound Measurements of Jet A and S-8 Aviation Turbine Fuels†

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Received October 14, 2008. Revised Manuscript Received December 17, 2008

The density and speed of sound were measured for three samples of aviation jet fuel A and a synthetic fuel (S-8) derived from the Fischer−Tropsch process. Measurements of density and speed of sound were carried out at ambient pressure (83 kPa) with a rapid characterization instrument from 278.15 to 343.15 K. Density measurements of the compressed liquids ranged from 270 to 470 K with pressures to 30 MPa. A total of 529 experimental points are reported. The density measurements are correlated within 0.1% with a modified Tait equation, and adiabatic compressibilities are derived from the density and speed of sound data at ambient pressure.

1. Introduction

The United States Department of Defense is interested in fielding a generic fuel that would be similar to the current military aviation jet fuel JP-8 and that could be used to power everything from planes to tanks and other ground vehicles. In conjunction, environmental concerns and the desire to become more energy independent have led to the development of a synthetic fluid S-8 (CAS 437986-20-4) produced from natural gas by the Fischer−Tropsch process, as a blending stock for JP-8. The major chemical constituents of JP-8 are nearly identical to those of Jet A, the most common commercial gas turbine fuel. In this work, we have studied three different samples of Jet A and one of S-8. These fluids are complex hydrocarbon mixtures whose properties cannot be predicted with sufficient accuracy by present models or simulation. Density and speed of sound were measured for the three Jet A samples and for S-8 to provide data necessary to formulate equations of state to correlate the fluid properties and thus facilitate the optimization of future military fuels.

The measurements reported here are part of a comprehensive project to characterize fuels and rocket propellants.[1] Tabulated results of density and speed of sound measurements for the three Jet A samples and S-8 are given. Density is an important fuel parameter directly related to aircraft range. Speed of sound is required in some aircraft fuel gauging systems for proper operation. Adiabatic compressibilities have been derived from the ambient pressure density and speed of sound data and are also included in the tables. Compressed liquid density data have been extrapolated to 83 kPa and combined with ambient pressure density data to correlate a Rackett equation for density. Additionally, the compressed liquid density data have been correlated with a Tait equation. Parameters for all of the correlations are reported.

2. Sample Liquids

The four fuel samples measured in this work were provided by the Fuels Branch of the Air Force Research Laboratory, Wright-Patterson Air Force Base, Dayton, OH. A detailed discussion of composition and distillation curves for each of the samples is described by Smith and Bruno.[2] The three Jet A samples are designated as POSF-3638, -3602, and -4658 and represent a range of different compositions that are consistent with the specifications for Jet A and JP-8. From a review of ref 2, it is readily apparent that these specifications allow for relatively significant differences in composition. The numerical designations serve only to identify an individual fluid and have no significance with regard to composition. The sample labeled POSF-4658 is considered to be the most representative of the three Jet A samples, because it is a composite of several available batches of Jet A, obtained from multiple manufacturers and mixed in approximately equal volume aliquots. For example, the aromatic content of the 4658 fuel is very close to the Jet A/JP-8 average.[3] The S-8 sample was produced from natural gas by the Fischer−Tropsch process and consists of C_7-C_{18} linear and branched alkanes. A detailed description of the analysis and the composition of the Jet A 4658 and S-8 samples is given by Bruno et al.[4] Testing carried out in accordance with American Society for Testing and Materials (ASTM) D-2789

† Disclaimer: 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 (NIST) nor does it imply that the particular product or equipment is necessarily the best available for the purpose.

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(1) Outcalt, S. L.; Laesecke, A.; Brumback, K. J. Thermophysical properties measurements of rocket propellants RP-1 and RP-2. *J. Propul. Power* **2009**, manuscript submitted.

(2) Smith, B. L.; Bruno, T. J. Improvements in the measurement of distillation curves. 4. Application to the aviation turbine fuel Jet-A. *Ind. Eng. Chem. Res.* **2007**, *26*, 310–320.

(3) World Fuel Sampling Program, CRC Report 647. Coordination Research Council, Alpharetta, GA, June 2006.

(4) Bruno, T. J.; Laesecke, A.; Outcalt, S. L.; Seelig, H. D.; Smith, B. L. Properties of a 50/50 Mixture of Jet-A + S-8. U.S. Department of Commerce, Washington, D.C., 2007; p 32.

10.1021/ef800888q
Published on Web 01/27/2009

Table 1. Density, Speed of Sound, and Adiabatic Compressibility of the Fuels Measured in the Density and Sound Speed Analyzer[a]

temperature, T (K)	density, ρ (kg m^{-3})	speed of sound, w (m s^{-1})	adiabatic compressibility, κ_S (T Pa^{-1})	density, ρ (kg m^{-3})	speed of sound, w (m s^{-1})	adiabatic compressibility, κ_S (T Pa^{-1})
		Jet A 3602			Jet A 3638	
278.15	827.3	1385.6	629.63	804.2	1364.3	668.03
283.15	823.6	1365.4	651.27	800.4	1344.0	691.68
293.15	816.3	1325.9	696.85	792.8	1304.3	741.45
303.15	808.9	1287.2	746.15	785.3	1265.3	795.38
313.15	801.5	1249.2	799.57	777.8	1227.0	853.99
323.15	794.1	1211.8	857.53	770.3	1189.2	917.93
333.15	786.7	1175.2	920.49	762.8	1151.9	988.03
343.15	779.2	1139.5	988.49	755.2	1115.4	1064.4
		Jet A 4658			S-8	
278.15	814.1	1376.8	648.04	762.9	1336.0	734.35
283.15	810.4	1356.5	670.56	759.2	1315.7	761.04
293.15	803.1	1317.0	717.90	751.5	1275.7	817.73
303.15	795.8	1278.3	769.06	744.0	1236.4	879.21
313.15	788.4	1240.2	824.68	736.6	1197.9	946.13
323.15	781.0	1202.7	885.19	729.2	1160.0	1019.1
333.15	773.6	1165.8	951.02	721.7	1122.8	1099.0
343.15	766.2	1130.0	1022.1	714.2	1086.3	1186.5

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

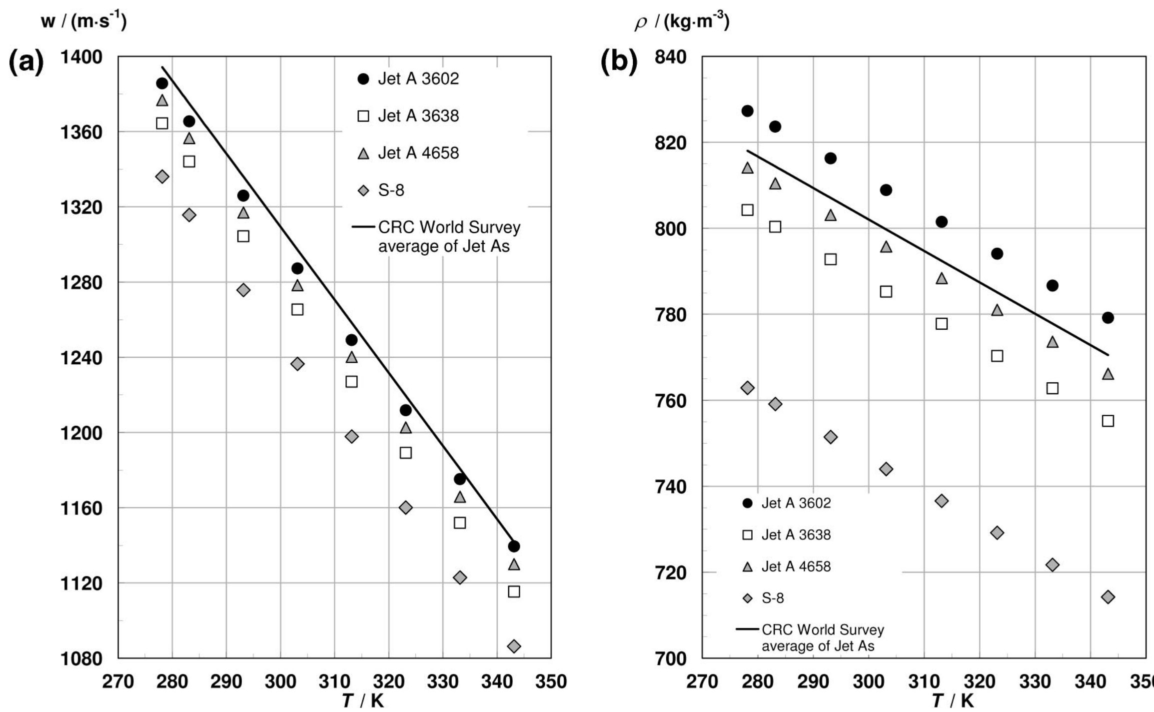


Figure 1. Measured (a) speed of sound data and (b) density data of the three Jet A samples and S-8 as a function of the temperature at an ambient pressure of 0.083 MPa and the correlation for the speed of sound and density of Jet A from ref 3.

is reported in ref 2 and shows the S-8 sample to be predominantly paraffins (80% by volume), while Jet A 4658 was more diverse, with its major components being 46.5% paraffins, 22.5% monocycloparaffins, and 18.4% alkyl aromatics. The composition of the Jet A 3638 sample was similar to that of Jet A 4658 but with the smallest amount of alkyl aromatics of the three Jet A samples. The Jet A 3602 sample had a similar volume fraction of monocycloparaffins but a smaller amount of paraffins (36.0% by volume) and a larger amount of alkyl aromatics compared to the other two Jet A samples.

3. Experimental Section

A density and sound speed analyzer DSA 5000 from Anton Paar Company was used to measure these properties at ambient pressure. Details of the instrument and experimental procedures have been reported in Laesecke and Outcalt et al.,[5] and thus, only a brief description will be given here. Temperature scans were programmed from 70 to 10 °C, in decrements of 10 °C, followed by a single measurement at 5 °C. The device contains a sound speed cell and a vibrating quartz tube densimeter in series. The temperature is measured with an integrated Pt-100 thermometer, with an estimated uncertainty of 0.01 K. The instrument was calibrated with air and deionized water at 20 °C. The reproducibility of the sound speed of water at 20 °C to within 0.01% was checked before and after measurements of the fuel samples. Fresh samples of test liquids were injected for each temperature scan instead of performing repetitive measurements on the same sample. At least four temperature scans were performed for each test liquid. The relative standard deviation of these repeated sound speed measurements

(5) Laesecke, A.; Outcalt, S. L.; Brumback, K. J. Density and speed of sound measurements of methyl- and propylcyclohexane. *Energy Fuels* **2008**, *22*, 2629–2636.

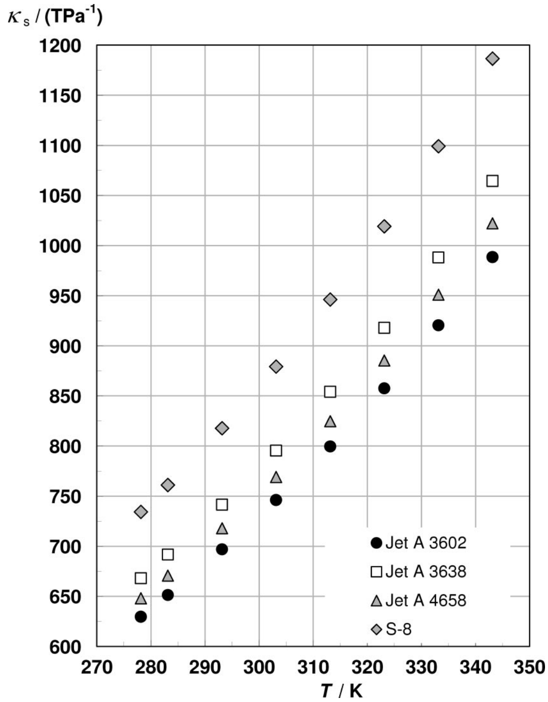


Figure 2. Adiabatic compressibility data of the three Jet A compositions and S-8 as a function of the temperature at ambient pressure. Values were calculated from the measured density and speed of sound data.

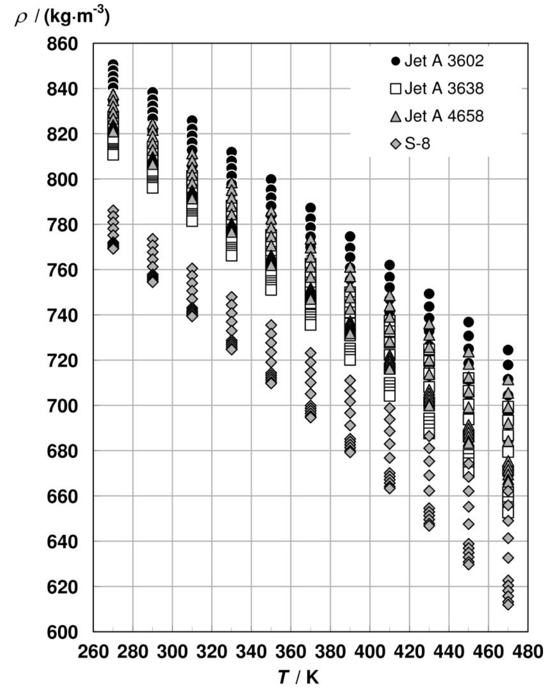


Figure 3. Measured compressed liquid density data of the three Jet A samples and S-8 as a function of the temperature. Along the isotherms, the highest density corresponds to 30 MPa and the lowest density corresponds to 0.5 MPa.

was lower than 0.04%. The manufacturer's quoted uncertainty of sound speed measurements with this instrument is 0.1%.

Densities of the test liquids were measured in accordance with ASTM D4052 standard test method[6] during the same temperature scans that were carried out to obtain the speeds of sound. The instrument corrects the measured densities for the viscosity of the test liquid. The relative standard deviation of repeated density measurements was lower than 0.02%.

Density measurements of the compressed test liquids were made with the automated densimeter of Outcalt and McLinden, details of which have been described in a previous publication.[7] Central to the apparatus is a commercial vibrating-tube densimeter DMA-HPM from Anton Paar Company. Several 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. The temperature range of the instrument is 270−470 K, with pressures up to 50 MPa. In this work, we measured 11 isotherms over the range of 0.5−30 MPa for each of the samples. The instrument was calibrated with propane and toluene over the entire temperature and pressure range. The

Table 2. Compressed Liquid Densities of Jet A 3602 Measured in the High-Pressure Vibrating-Tube Densimeter along Isotherms from 270 to 470 K[a]

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})
270 K		290 K		310 K		330 K		350 K		370 K	
30.77	850.5	31.57	838.3	31.93	825.8	31.64	812.2	32.10	799.8	31.93	787.1
25.61	847.9	25.59	835.0	25.57	822.0	25.59	808.2	25.63	795.3	25.70	782.4
20.66	845.3	20.65	832.2	20.76	819.0	20.81	804.9	20.88	791.7	20.96	778.6
15.93	842.8	15.97	829.5	16.00	816.0	16.08	801.5	16.08	788.0	16.11	774.5
11.31	840.3	11.24	826.6	11.2	812.7	11.18	797.9	11.11	784.0	11.02	769.9
6.06	837.3	5.97	823.3	5.76	808.8	5.77	793.7	5.60	779.2	5.49	764.6
4.92	836.6	4.78	822.5	4.67	808.0	4.59	792.8	4.48	778.2	4.35	763.5
3.74	835.9	3.60	821.7	3.50	807.1	3.41	791.8	3.28	777.1	3.23	762.3
2.52	835.2	2.42	821.0	2.30	806.1	2.26	790.9	2.21	776.1	2.16	761.2
1.32	834.4	*0.083*	*819.4*	1.72	805.7	1.12	789.9	1.10	775.1	1.09	760.1
0.083	*833.7*			*0.083*	*804.4*	0.54	789.4	0.56	774.6	0.59	759.5
						0.083	*737.1*	*0.083*	*774.1*	*0.083*	*759.0*
390 K		410 K		430 K		450 K		470 K			
31.81	774.6	31.75	762.0	31.66	749.3	31.67	736.8	31.63	724.4		
25.74	769.5	25.84	756.6	25.87	743.6	25.93	730.6	26.01	717.9		
21.01	765.4	21.03	752.0	21.04	738.6	21.03	725.0	20.98	711.5		
16.08	760.8	16.04	746.9	15.97	732.8	15.90	718.6	15.85	704.4		
10.88	755.6	10.78	741.1	10.65	726.3	10.57	711.3	10.52	696.2		
5.41	749.8	5.33	734.5	5.30	719.1	5.32	703.2	5.39	687.3		
4.28	748.5	4.28	733.2	4.26	717.5	4.33	701.6	4.39	685.4		
3.24	747.3	3.21	731.8	3.26	716.1	3.33	699.9	3.40	683.5		
2.16	746.0	2.19	730.4	2.24	714.5	2.35	698.2	2.41	681.5		
1.26	744.9	1.19	729.1	1.27	713.0	1.34	696.4	1.43	679.5		
0.66	744.2	*0.083*	*727.6*	*0.083*	*711.1*	*0.083*	*694.1*	*0.083*	*676.6*		
0.083	*743.5*										

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

overall uncertainty ($k = 2$) in density is 0.64−0.81 kg m^{-3}, corresponding to a relative uncertainty in density of 0.07−0.14%.

4. Results

Table 1 lists values of density, speed of sound, and derived adiabatic compressibilities for the three Jet A samples and S-8 at ambient pressure from 278.15 to 343.15 K. Adiabatic compressibilities were calculated from the measured densities and speeds of sound via the thermodynamic relation

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

where V denotes the volume, p is the pressure, ρ is the density, and w is the speed of sound. The subscript s indicates "at constant entropy". The data for the speed of sound, ambient density, and adiabatic compressibility are depicted graphically in parts a and b of Figure 1 and Figure 2, respectively. It can be seen in Figures 1 and 2 that the Jet A 3638 sample has thermodynamic properties at atmospheric pressure that are most similar to S-8. It can also be seen in Figure 1 that given the

Table 3. Compressed Liquid Densities of Jet A 3638 Measured in the High-Pressure Vibrating-Tube Densimeter along Isotherms from 270 to 470 K[a]

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})
270 K		290 K		310 K		330 K		350 K		370 K	
30.05	827.1	30.08	814.1	30.08	801.4	30.04	788.3	30.06	775.3	30.05	762.5
25.10	824.5	25.14	811.3	25.13	798.3	25.11	784.9	25.12	771.7	25.12	758.5
20.15	821.8	20.19	808.4	20.18	795.1	20.16	781.4	20.16	767.8	20.16	754.3
15.16	819.1	15.20	805.4	15.19	791.8	15.17	777.7	15.18	763.8	15.18	749.9
10.13	816.2	10.18	802.2	10.16	788.3	10.15	773.8	10.16	759.5	10.16	745.2
5.06	813.2	5.11	798.2	5.09	784.5	5.08	769.7	5.09	754.9	5.09	740.0
4.04	812.6	4.09	798.2	4.08	783.8	4.07	768.8	4.07	753.9	4.07	738.9
3.02	812.0	3.07	797.5	3.05	783.0	3.05	767.9	3.06	753.0	3.05	737.8
1.99	811.3	2.05	796.8	2.03	782.2	2.03	767.0	2.04	752.0	2.03	736.7
0.97	810.7	1.03	796.1	1.01	781.4	1.01	766.1	1.02	751.0	1.01	735.5
0.083	*810.0*	*0.083*	*795.4*	*0.083*	*780.6*	*0.083*	*765.3*	*0.083*	*750.0*	*0.083*	*734.5*
390 K		410 K		430 K		450 K		470 K			
30.02	750.0	30.02	737.4	30.01	724.7	29.96	712.0	29.94	699.4		
25.08	745.6	25.08	732.7	25.07	719.6	25.02	706.4	25.00	693.3		
20.13	741.0	20.13	727.7	20.11	714.1	20.07	700.4	20.05	686.7		
15.16	736.1	15.15	722.3	15.13	708.1	15.10	693.8	15.08	679.4		
10.14	730.9	10.13	716.4	10.11	701.5	10.08	686.4	10.06	671.1		
5.08	725.1	5.07	709.9	5.05	694.2	5.02	678.1	5.00	661.5		
4.06	723.9	4.05	708.5	4.03	692.6	4.00	676.3	3.98	659.4		
3.05	722.6	3.03	707.1	3.01	691.0	2.99	674.4	2.96	657.2		
2.03	721.4	2.01	705.7	1.99	689.3	1.96	672.5	1.94	655.0		
1.01	720.1	0.99	704.2	0.96	687.6	0.94	670.4	0.92	652.6		
0.083	*718.9*	*0.083*	*702.8*	*0.083*	*686.1*	*0.083*	*668.7*	*0.083*	*650.07*		

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

Table 4. Compressed Liquid Densities of Jet A 4658 Measured in the High-Pressure Vibrating-Tube Densimeter along Isotherms from 270 to 470 K[a]

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})
270 K		290 K		310 K		330 K		350 K		370 K	
30.02	837.4	30.00	824.5	30.01	811.3	30.00	798.5	30.00	786.0	30.01	773.6
25.01	834.8	25.00	821.7	25.01	808.2	25.01	795.2	25.01	782.4	25.01	769.7
20.00	832.2	20.00	818.8	20.01	805.1	20.01	791.7	20.01	778.7	20.01	765.6
15.01	829.5	15.00	815.8	15.01	801.8	15.01	788.1	15.01	774.7	15.01	761.3
10.01	826.7	10.00	812.8	10.01	798.4	10.01	784.3	10.01	770.6	10.02	756.7
5.00	823.8	5.01	809.6	5.01	794.8	5.01	780.4	5.01	766.2	5.01	751.8
4.01	823.2	4.01	808.9	4.00	794.1	4.02	779.6	4.01	765.3	4.01	750.8
3.00	822.6	3.01	808.3	3.01	793.3	3.01	778.8	3.01	764.4	3.01	749.8
2.01	822.0	2.01	807.6	2.01	792.6	2.01	777.9	2.01	763.4	2.01	748.7
1.01	821.4	1.01	806.9	1.01	791.8	1.01	777.1	1.01	762.5	1.01	747.6
0.51	821.1	0.51	806.6	0.51	791.4	0.51	776.6	0.50	762.0	0.50	746.1
0.083	*820.8*	*0.083*	*806.3*	*0.083*	*791.1*	*0.083*	*776.3*	*0.083*	*761.6*	*0.083*	*746.6*
390 K		410 K		430 K		450 K		470 K			
30.01	761.2	30.00	748.7	30.00	736.2	30.00	723.8	29.99	711.5		
25.01	756.9	25.01	744.0	25.01	731.2	25.00	718.3	25.00	705.6		
20.02	752.4	20.01	739.9	20.01	725.8	20.01	712.5	20.01	699.2		
15.01	747.7	15.00	735.3	15.01	720.0	15.00	706.1	15.02	692.1		
10.01	742.6	10.01	728.3	10.02	713.8	10.00	699.1	10.02	684.3		
5.01	737.2	5.01	722.2	5.01	706.9	5.02	691.4	5.01	675.5		
4.01	736.0	4.01	720.9	4.02	705.4	4.00	689.7	4.00	673.5		
3.01	734.9	3.01	719.5	3.00	703.9	3.01	688.0	3.00	671.5		
2.00	733.7	2.00	718.2	2.01	702.4	2.01	686.2	2.01	669.5		
1.01	732.5	1.01	716.9	1.01	700.8	1.01	684.4	1.01	667.4		
0.50	731.8	0.52	716.2	0.51	700.0	0.51	683.4	0.51	666.3		
0.083	*731.3*	*0.083*	*715.6*	*0.083*	*699.3*	*0.083*	*682.6*	*0.083*	*665.3*		

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

Table 5. Compressed Liquid Densities of S-8 Measured in the High-Pressure Vibrating-Tube Densimeter along Isotherms from 270 to 470 K[a]

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})
270 K		290 K		310 K		330 K		350 K		370 K	
30.09	786.2	30.04	773.6	29.97	760.5	30.00	747.9	30.0 1	735.5	30.02	723.2
25.15	783.6	25.10	770.7	25.03	757.3	25.01	744.4	25.01	731.7	25.02	719.0
20.20	780.9	20.14	767.7	20.07	754.0	20.01	740.8	20.01	727.7	20.01	714.7
15.21	778.1	15.15	764.6	15.09	750.6	15.01	737.0	15.00	723.5	15.02	710.1
10.19	775.1	10.13	761.3	10.07	747.0	10.01	733.0	10.01	719.1	10.00	705.1
5.12	772.1	5.06	757.8	5.00	743.1	5.01	728.7	5.00	714.3	5.01	699.9
4.10	771.4	4.05	757.1	3.98	742.3	4.01	727.9	4.01	713.4	4.01	698.8
3.07	770.8	3.02	756.4	2.96	741.5	3.01	727.0	3.01	712.3	3.01	697.6
2.05	770.1	2.00	755.6	1.94	740.7	2.01	726.1	2.00	711.3	2.00	696.4
1.02	769.5	0.97	754.9	0.92	739.8	1.01	725.1	1.01	710.3	1.01	695.3
0.51	769.1	0.46	754.5	0.40	739.4	0.51	724.7	0.50	709.8	0.50	694.7
0.083	*768.9*	*0.083*	*754.2*	*0.083*	*739.1*	*0.083*	*724.3*	*0.083*	*709.3*	*0.083*	*694.2*
390 K		410 K		430 K		450 K		470 K			
30.02	711.0	30.01	698.7	29.99	686.4	30.02	674.3	30.01	662.2		
25.00	706.5	25.01	693.8	25.02	681.1	25.01	668.4	25.01	655.9		
20.01	701.7	20.01	688.6	20.00	675.3	20.02	662.1	20.01	649.0		
15.01	696.6	15.00	683.0	15.00	669.1	15.00	655.2	15.01	641.3		
10.00	691.1	10.01	676.9	10.01	662.2	10.00	647.5	10.01	632.6		
5.00	685.2	5.00	670.1	5.00	654.6	5.01	638.8	5.01	622.7		
4.00	683.9	4.00	668.7	4.01	653.0	4.00	636.9	4.02	620.5		
3.00	682.6	3.00	667.2	3.01	651.3	3.00	634.9	3.01	618.1		
2.01	681.3	2.01	665.7	2.00	649.5	2.01	632.9	2.00	615.7		
1.00	680.0	1.00	664.1	1.01	647.7	1.01	630.8	1.00	613.2		
0.50	679.3	0.50	663.3	0.49	646.8	0.50	629.7	0.50	611.9		
0.083	*678.7*	*0.083*	*662.7*	*0.083*	*646.0*	*0.083*	*628.8*	*0.083*	*610.8*		

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

Table 6. Parameters of the Correlations for the Speed of Sound of the Three Jet A Samples and S-8 at Ambient Pressure of 0.083 MPa and Temperatures from 278.15 to 343.15 K[a]

parameter	value	standard deviation	value	standard deviation
	Jet A 3602		Jet A 3638	
β_1 (m s^{-1})	2789.1860	5.8	2727.3236	8.6
β_2 (m s^{-1} K^{-1})	−6.0683741	3.7×10^{-2}	−5.7684925	5.6×10^{-2}
β_3 (m s^{-1} K^{-2})	3.6737339×10^{-3}	6.0×10^{-5}	3.1239530×10^{-3}	9.0×10^{-5}
AAD (%)		3.7×10^{-3}		5.7×10^{-3}
rms (%)		4.2×10^{-3}		6.2×10^{-3}
	Jet A 4658		S-8	
β_1 (m s^{-1})	2771.1969	8.9	2738.2926	4.1
β_2 (m s^{-1} K^{-1})	−6.0012041	5.7×10^{-2}	−6.0152111	2.7×10^{-2}
β_3 (m s^{-1} K^{-2})	3.5504567×10^{-3}	9.3×10^{-5}	3.5002921×10^{-3}	3.4×10^{-8}
AAD (%)		6.0×10^{-3}		2.7×10^{-3}
rms (%)		6.5×10^{-3}		3.0×10^{-3}

[a] Average absolute deviations and root mean square deviations are given to indicate the quality of the correlations.

Table 7. Parameters of the Rackett Correlations for the Density of Three Jet A Compositions and S-8 at Ambient Pressure of 83 kPa and Temperatures from 270 to 470 K

parameter	value	standard deviation	value	standard deviation
	Jet A 3602		Jet A 3638	
β_4 (kg m^{-3})	287.67132	0.100	280.19930	0.054
β_5	0.52969387	9.1×10^{-5}	0.52863542	4.9×10^{-5}
β_6 (K)	574.26287	0.065	559.63279	0.033
β_7	0.62113263	1.3×10^{-4}	0.61879511	7.5×10^{-5}
	Jet A 4658		S-8	
β_4 (kg m^{-3})	287.67122	0.148	273.71023	0.057
β_5	0.53272953	1.3×10^{-4}	0.53377090	5.4×10^{-5}
β_6 (K)	574.26277	0.103	544.31655	0.037
β_7	0.64481646	2.0×10^{-4}	0.64102711	8.8×10^{-5}

possible variations in sample composition, our measurements are reasonably consistent with Jet A correlations from the CRC World Survey.[3]

Listed in Tables 2−5 are measured values of compressed liquid density from 270 to 470 K with pressures to 30 MPa for Jet A 3602, Jet A 3638, Jet A 4658, and S-8, respectively. Also listed are density values extrapolated to 83 kPa (this is the approximate atmospheric pressure in Boulder, CO) for each temperature. These were obtained by fitting a second-order polynomial to the isothermal data at pressures less than or equal to 10 MPa and extrapolating to 83 kPa. 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. Measured compressed liquid densities of all four fuels are plotted in Figure 3 to illustrate how they compare to one another.

5. Correlation of Data

The speed of sound data at atmospheric pressure were correlated as a function of the temperature with the second-order polynomial

$$w = \beta_1 + \beta_2 T + \beta_3 T^2 \qquad (2)$$

The symbol w denotes the speed of sound in units of m s^{-1}, and T is the absolute temperature in Kelvin. The values of the adjustable parameters β_1−β_3 and their standard deviations are listed in Table 6 for all four of the test liquids. The listed

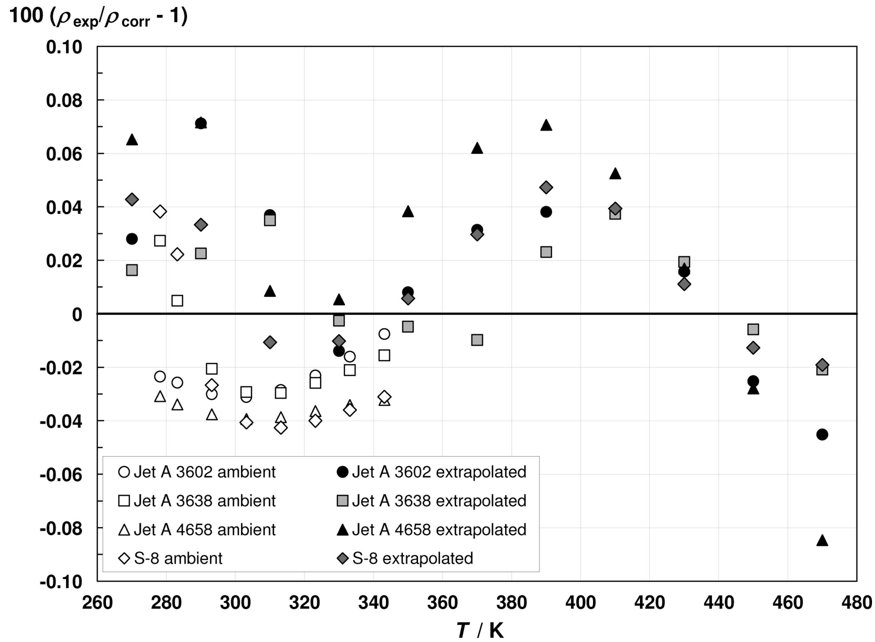


Figure 4. Deviations of measured and extrapolated ambient pressure density data of the three Jet A compositions and S-8 from the Rackett correlations.

Table 8. Parameters of the Tait Correlations for the Density of Three Jet A Compositions and S-8 in Terms of Temperature and Pressure

parameter	value	standard deviation	value	standard deviation
	Jet A 3602		Jet A 3638	
C	79.019261×10^{-3}	2.1×10^{-4}	79.563634×10^{-3}	1.2×10^{-4}
β_8	320.08985	1.0	319.99780	0.59
β_9	−284.95609	1.1	−291.41934	0.61
β_{10}	65.772865	0.30	68.515342	0.17
	Jet A 4658		S-8	
C	79.505617×10^{-3}	2.9×10^{-4}	79.91734×10^{-3}	1.5×10^{-4}
β_8	323.45807	1.4	300.92000	0.69
β_9	−294.55363	1.4	−278.22110	0.73
β_{10}	70.165368	0.41	66.270142	0.21

parameters fit the data well within their experimental uncertainty. The correlations were tested up to 470 K and found to provide reasonable extrapolation behavior up to that temperature.

Density measurements at ambient pressure and values extrapolated to 83 kPa from measured compressed liquid data were correlated with the Rackett equation to check the repeatability of the instruments and the consistency of our data in the combined temperature range of 270−470 K. The Rackett equation is written as

$$\rho = \beta_4 \beta_5^{-(1+(1-T/\beta_6)^{\beta_7})} \qquad (3)$$

Table 7 lists the Rackett correlation parameters for the Jet A samples and S-8. In Figure 4, the correlations serve 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 stated uncertainty of the density measurements.

To make the present results immediately usable for engineering and design purposes, the compressed liquid density data were correlated with a Tait equation similar to that of Dymond and Malhotra.[8] The temperature dependence of the parameter C was omitted because it was not needed to fit the data within their experimental uncertainty. The equation used to fit the compressed liquid density data reads

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

where $\rho_{\mathrm{ref}}(T)$ is the temperature-dependent density at the reference pressure $p_{\mathrm{ref}} = 0.083$ MPa from eq 2. The temperature dependence of the Tait parameter $B(T)$ was expressed by a quadratic polynomial

$$B(T) = \beta_8 + \beta_9 T_r + \beta_{10} T_r^2 \qquad (5)$$

where T_r is the absolute temperature T divided by 273.15 K. Parameters for the Tait correlations are given in Table 8. Parts a−d of Figure 5 show deviations of the measured compressed liquid density data from baselines that represent the Tait correlations for Jet A 3602, Jet A 3638, Jet A 4658, and S-8, respectively. These correlations represent our data with AADs of 0.015−0.031%, which is well within the stated uncertainty. Previous work[5] showed that the Tait equation can be extrapolated to 100 MPa without loss of accuracy. Variations in the composition of Jet A samples are a real concern in terms of developing an accurate equation of state to generically represent the fuel. That task however is not the intent of the correlations presented here.

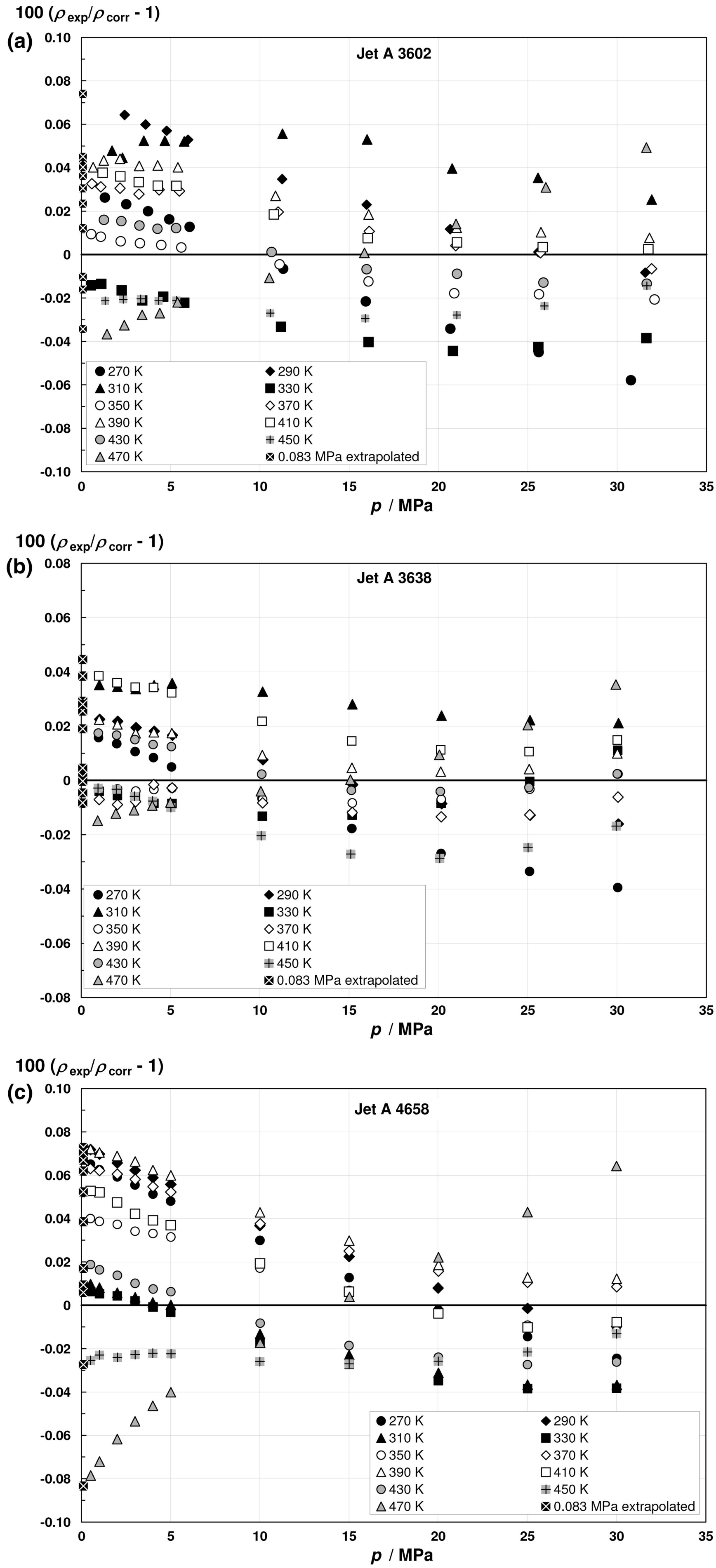
6. Conclusions

Density and speed of sound at ambient pressure and compressed liquid densities of three Jet A samples and S-8 have been measured covering a temperature range of 270−470 K with pressures to 30 MPa. The density data have been correlated with a modified Tait equation within their experimental uncertainty of 0.1%, and the speed of sound data at ambient pressure were correlated with a second-order

(6) American Society for Testing of Materials (ASTM), West Conshohocken, PA.

(7) Outcalt, S. L.; McLinden, M. O. Automated densimeter for the rapid characterization of industrial fluids. *Ind. Eng. Chem. Res.* **2007**, *46*, 8264–8269.

(8) Dymond, J. H.; Malhotra, R. The Tait equation: 100 years on. *Int. J. Thermophys.* **1988**, *9* (6), 941–951.


100 (ρexp/ρcorr - 1)
(a)
Jet A 3602
270 K
290 K
310 K
330 K
350 K
370 K
390 K
410 K
430 K
450 K
470 K
0.083 MPa extrapolated
p / MPa
100 (ρexp/ρcorr - 1)
(b)
Jet A 3638
270 K
290 K
310 K
330 K
350 K
370 K
390 K
410 K
430 K
450 K
470 K
0.083 MPa extrapolated
p / MPa
100 (ρexp/ρcorr - 1)
(c)
Jet A 4658
270 K
290 K
310 K
330 K
350 K
370 K
390 K
410 K
430 K
450 K
470 K
0.083 MPa extrapolated
p / MPa

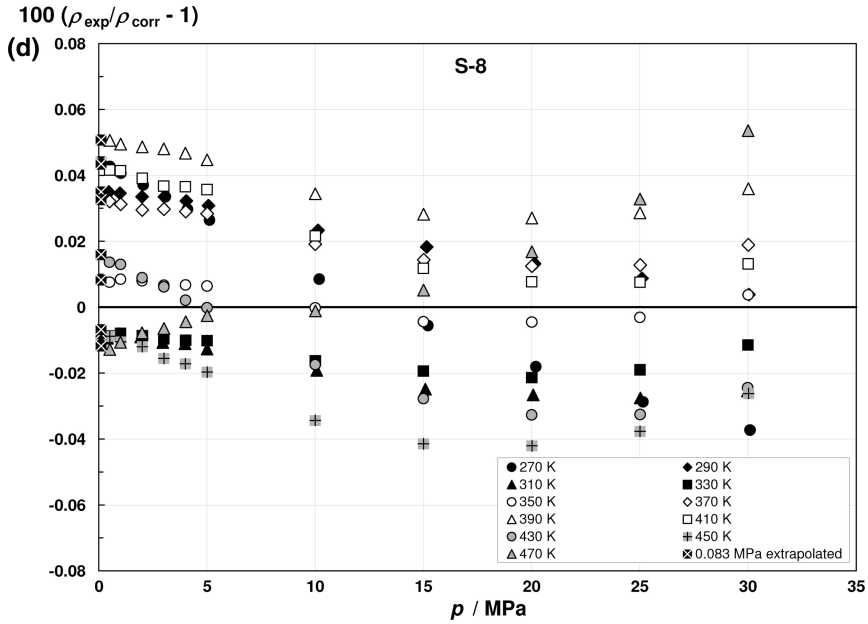


Figure 5. (a) Deviations of the density data of compressed liquid (a) Jet A 3602, (b) Jet A 3638, (c) Jet A 4658, and (d) S-8 from the Tait correlations.

polynomial in the temperature within the experimental uncertainty of 0.1%. The general composition of each of the samples has been described, and it can be seen that the properties of density and speed of sound reported here are relatively similar (within 4% in density and 2% in speed of sound) for the three Jet A samples. The S-8 sample exhibited somewhat smaller values of both density and speed of sound as compared to the Jet A samples, but this is not unexpected because synthetic fuels are known for their high hydrogen content and, thus, lower densities.[3] Our measurements are consistent with previously published data.

Acknowledgment. We acknowledge the financial support of the Air Force Research Laboratory (MIPR F4FBEY5102G001) and the Air Force Office of Scientific Research (MIPR F1ATA06004G004). We also acknowledge Tim Edwards for suggestions that improved the manuscript.

EF800888Q