Density, Speed of Sound, and Viscosity Measurements of Alternative Aviation Turbine Fuels*

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High fuel costs, the need to secure supply chains, and environmental concerns, have all led to an increasing interest in nonpetroleum sources such as natural gas, coal, and biomass, as potential alternatives to petroleum based aviation fuel feedstocks. Synthetic isoparaffinic kerosenes (S-IPK) are one such alternative. In this paper, we present density, speed of sound, and viscosity measurements for two S-IPK fuels. Measurements of density and speed of sound were carried out at ambient pressure (83 kPa) from 278 K to 343 K. A second instrument was also used to measure density of the compressed liquids from 270 K to 470 K with pressures up to 50 MPa. Viscosity measurements were carried out at ambient pressure from 263 K to 373 K. Data for all three properties are compared to data taken previously for another synthetic aviation fuel, S-8, and for two petroleum based Jet A fuels.

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Introduction

Traditionally, the most common military and civilian aviation turbine fuels used in the United States have been JP-8 and Jet-A, respectively. The two fuels are virtually identical apart from the additive package that is blended with Jet-A to create JP-8. However, in recent years, there has been increasing interest in the expansion of aviation fuel feedstocks to include nonpetroleum sources such as natural gas, coal, and biomass. High fuel costs, the need to secure supply chains, and environmental concerns, are all driving factors for this interest.

Synthetic isoparaffinic kerosenes (S-IPK) are among the most promising alternatives.[1] Typically, S-IPK fluids are created by catalytically converting a synthesis gas into liquid hydrocarbons using the Fischer-Tropsch (FT) process.[2] The synthesis gas itself is a product of the controlled combustion of natural gas, coal, or biomass. Perhaps the most familiar FT aviation fuel to date, S-8, is derived from natural gas and is a synthetic substitute for JP-8, composed primarily of C7 to C18 linear and branched alkanes.[3-6]

Extensive studies of JP-8/Jet-A and S-8 have previously been presented[3-8] as part of an ongoing comprehensive project within the Thermophysical Properties Division of the National Institute of Standards and Technology (NIST). The goal of this project is to characterize the thermodynamic, transport, and chemical properties of aviation fuels in an effort to facilitate enhancements in design and operational specifications and the development of new applications. In this paper, we compare the densities, speeds of sound, and viscosities of two new S-IPK fluids with S-8 and Jet-A. The first is another natural gas derived fluid, henceforth referred to as GTL. The second S-IPK fluid is derived from coal and henceforth will be referred to as CTL.

Experimental

Fuel Samples. Samples of aviation fuels discussed herein were obtained from the Air Force Research Laboratory at Wright Patterson Air Force Base in Ohio. All samples were measured as they were received. Although the FT processes and resulting mixtures for GTL and CTL differ, the final S-IPK products are similar in composition. Both are predominantly composed of paraffins, monocycloparaffins, and dicycloparaffins. Additional information about the production and composition of GTL and CTL can be found in *Bruno et al.*[9]

Density Measurements. Compressed density measurements were made with an automated densimeter, the details of which can be found in *Outcalt and McLinden*[10]. At the core of the apparatus is a commercial vibrating-tube densimeter, which is housed in a custom designed thermostat to maximize temperature stability and control. Additionally, several physical and procedural improvements have been implemented to minimize measurement uncertainties. The temperature range of the instrument is 270 K to 470 K. In this work, we measured eleven isotherms over the range 0.5 MPa to 50 MPa for each of the samples. The instrument was calibrated with propane and toluene over the entire temperature and pressure range. The overall expanded uncertainty (k=2) in density is 0.64 kg·m⁻³ to 0.81 kg·m⁻³ corresponding to a relative uncertainty in density of 0.07 % to 0.14 %.

Density measurements at atmospheric pressure were made with a commercial density and sound speed analyzer that combines miniaturized inline cells to simultaneously measure these two properties. Details of the instrument and experimental procedures can be found in *Fortin et al*[11]. Briefly, the density cell contains a borosilicate glass vibrating tube and both measurement cells are housed in a thermostated block. In this work, five temperature scans were performed from 343 K to 278 K in 5 K decrements, with fresh aliquots of sample injected for each scan. The instrument was calibrated with water and toluene over the entire temperature range. The overall expanded uncertainty (k≈2.3) in density is 0.06 kg·m⁻³, corresponding to a relative uncertainty of 0.01 %.

Speed of Sound Measurements. The acoustic cell in the density and sound speed analyzer consists of a circular cavity 8 mm in diameter and 5 mm thickness sandwiched between two piezoelectric ultrasound transducers. By measuring the amount of time it takes for 3.5 MHz sound pulses to travel between transmitter and receiver, the speed of sound can be determined. The overall expanded uncertainty (k≈2.3) in speed of sound is 2.2 m·s⁻¹ to 3.7 m·s⁻¹, corresponding to a relative uncertainty of 0.2 % to 0.3 %.

Viscosity Measurements. Dynamic viscosity measurements at atmospheric pressure were made with a commercial viscodensimeter. Instrument details can be found in *Laesecke et al*[12]. Briefly, the viscometer consists of two horizontally mounted concentric cylinders housed in a thermostated copper block. Sample liquid is injected into the annular gap between the cylinders. During measurements, the outer cylinder is driven by an external motor at a constant rotational speed of 3,500 rpm. The resulting friction at the inner wall drags the sample liquid, and then the floating inner cylinder, into rotation. The viscosity is ultimately obtained from the ratio of revolutions for the two cylinders (outer/inner). In this work, five temperature scans were performed from 263 K to 373 K in 5 K increments, with fresh aliquots of sample injected for each scan. The instrument was calibrated with several certified viscosity standards covering the range from ~ 0.27 to ~ 1150 mPa·s. The overall expanded uncertainty (k≈2.3) in viscosity is .003 mPa·s to 0.03 mPa·s, corresponding to a relative uncertainty of 0.6 % to 1.9 %.

Results and Discussion

Compressed liquid densities as a function of temperature for both CTL and GTL are shown in **Figure 1**. At each temperature there are multiple data points corresponding to pressures from 0.5 to 30 MPa. The densities of CTL are approximately 3-5 % higher than those of GTL.
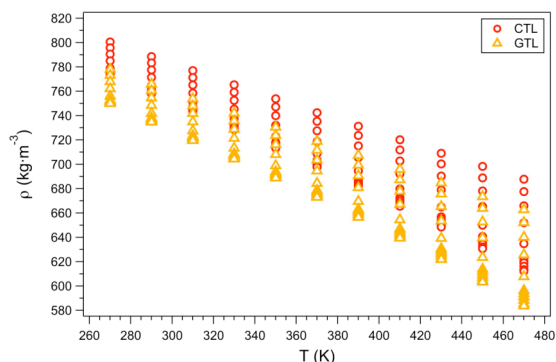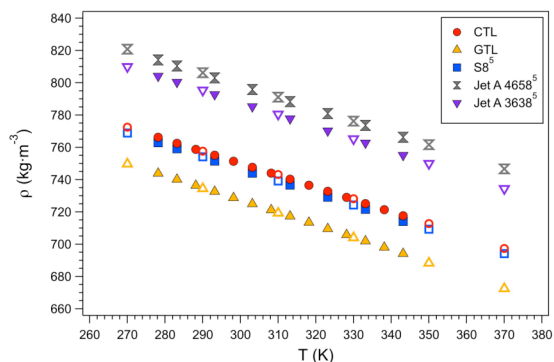

Figure 1. Compressed liquid density as a function of temperature. Along the isotherms, the highest density corresponds to 30 MPa and the lowest to 0.5 MPa.

Ambient pressure densities as a function of temperature for both CTL and GTL are shown as filled symbols in **Figure 2**. The open symbols also shown correspond to compressed liquid densities that

have been extrapolated to 83 kPa (the approximate atmospheric pressure in Boulder, CO). The two data sets agree within their experimental uncertainties. Again, CTL densities are higher than GTL densities by approximately 3-5 %.

Figure 2. Density as a function of temperature. Filled symbols represent ambient pressure measurements. Open symbols represent extrapolated compressed density measurements.

Also shown in **Figure 2** for comparison are ambient pressure and extrapolated compressed liquid densities for S8, Jet A 4658, and Jet A 3638.[5] The number designations of the two Jet A samples are for identification purposes only. Jet A 4658 is a composite made up of five different batches from different manufacturers and is thought to be representative of a typical Jet A fuel.[6-8] Jet A 3638 is unusual in that it is lower in aromatic content than is typical but yet it still meets fuel specifications.[6-8] Together, the two Jet A samples bracket the variability possible within Jet A fuel specifications. The similarity in the compositions of the two Jet A samples[6] is reflected in the relatively small (1 %) differences in their densities. Similarly, the differences in composition between the petroleum derived Jet A fuels and the natural gas and coal derived S-IPK fuels[6,9] are apparent in the significantly larger observed differences (5-9 %). What is perhaps most surprising is that the coal derived CTL, rather than the natural gas derived GTL, has densities that are most similar to S8. The densities of GTL are lower than those for S8 by approximately 3 %.
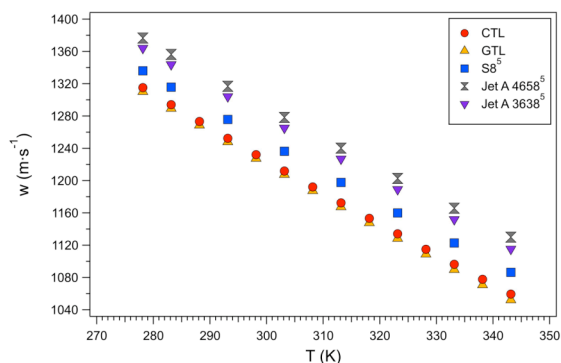
Figure 3. Speed of sound as a function of temperature.

Ambient pressure speeds of sound as a function of temperature are shown in **Figure 3**. Previously reported ambient pressure data[5] for Jet A 4658, Jet A 3638, and S8 are also shown for comparison. As was observed with the densities, the petroleum based Jet A fuels have significantly higher speed of sound values than either CTL or GTL, on the order of 4-7 %. The speeds of sound for the Jet A fuels are also higher than those for S8, although less significantly so (2-4 %). Unlike the densities, the speeds of sound of CTL and GTL are very similar and both are approximately 2-3 % lower than S8.

Figure 4 shows ambient pressure dynamic viscosities as a function of temperature. Once again, previously reported ambient pressure data for Jet A 4658, Jet A 3638, and S8 are also shown for comparison. With the viscosity data, the order has shifted significantly from what was observed with density and speed of sound. At 263 K, the highest viscosity sample is S8, whereas at 373 K, Jet A 4658 has the highest viscosity. The lowest viscosity sample is GTL at all temperatures. In fact, GTL is lower than all of the other four samples shown by 0.9-1.9 mPa·s at 263 K and 0.1-0.2 mPa·s at 373 K. In contrast, the spread among the other four samples is approximately 1.0 mPa·s at 263 K and 0.1 mPa·s at 373 K.
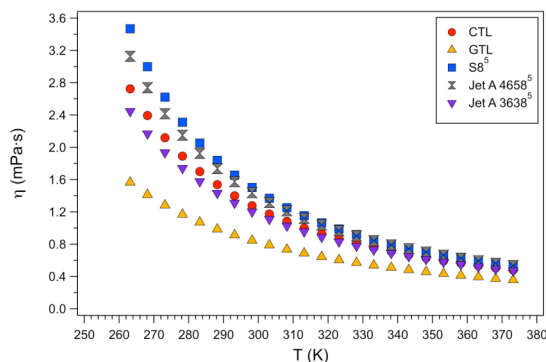
Figure 4. Dynamic viscosity as a function of temperature.

Conclusions

In this paper, we have presented both ambient pressure and compressed liquid densities for two alternative synthetic isoparaffinic kerosene turbine fuels, designated CTL and GTL. CTL is derived from coal, while GTL is derived from natural gas. Additionally, we have presented ambient pressure speeds of sound and dynamic viscosities for CTL and GTL. For all three properties, we compared the CTL and GTL to two petroleum based Jet A fuels that together cover the span of Jet A variability and to another natural gas derived S-IPK fuel, S8. The compositional differences in CTL and GTL compared with the Jet A fuels is readily apparent in both density and speed of sound but only GTL has a significantly different viscosity.

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