Published in final edited form as:

J Mol Liq. 2018 February ; 251: 128–141. doi:10.1016/j.molliq.2017.12.010.

Wide-ranging Absolute Viscosity Measurements of Sub- and Supercritical 1,1,1-trifluoroethane (R143a)¹

Arno Laesecke², Karsten Meier³, and Richard F. Hafer⁴

³Institut für Thermodynamik, Helmut-Schmidt-Universität/Universität der Bundeswehr Hamburg, Holstenhofweg 85, D-22043 Hamburg, Germany

⁴GlobalFoundries, 2070 Route 52, Hopewell Junction, NY 12533, U.S.A

Abstract

The viscosity of 1,1,1-trifluoroethane (R143a) was measured with a piezoelectrically actuated, torsionally vibrating quartz sensor. The measurements extended over a temperature range from 300 K to 440 K with pressures to 68 MPa and covered states from the dilute gas to the compressed liquid. The influence of the drive voltage on the torsional displacement of the vibrator in fluid and in vacuum was systematically investigated. Since R143a is highly polar, the sample conductance and susceptance were also monitored with the sensor to detect possible electroviscous contributions in the measured viscosities. None were identified so that the estimated uncertainty of the measurements remains at 2 % at a 95 % confidence level (coverage factor $k = 2$). The results agree well within this margin with literature data that were determined with four other viscometric techniques.

Keywords

1,1,1-trifluoroethane; measurements; polarity; R143a; torsional quartz vibrator viscometer; viscosity

1. Introduction

The torsional quartz vibrator viscometer (TQV) technique^{*)} has been used routinely in this laboratory since 1965 for absolute measurements whereas almost all other viscometers require calibration with viscosity standards. The first instrument for cryogenic temperatures below 320 K was described by Diller [1] and Haynes [2]. The second instrument for temperatures above ambient to 500 K was developed by Diller and Frederick [3]. The sensors in these viscometers are electromechanical vibrators where the sample is exposed to an alternating electric field. The possibility of electroviscous effects in measurements of

¹Contribution of the National Institute of Standards and Technology. Not subject to Copyright © in the U.S.A.

²Corresponding author. Arno.Laesecke@Boulder.NIST.Gov.

^{*)}We propose this new terminology for the technique. The previous name “torsional crystal viscometer (TCV)” did not sufficiently specify the material of the sensor (quartz) nor its motion (torsional vibration). The term “vibration” refers to an alternating deformation of the shape of an elastic solid while “oscillation” is more generally used for “regular variations in magnitude or position around a central point.” [A. Stevenson, C. A. Lindberg, New Oxford American Dictionary, Third Edition, OUP USA, 2010].

polar fluids with the TQV was first investigated by Meier [4] and demonstrated systematically by Laesecke [5].

This work continues here with measurements of 1,1,1-trifluoroethane ($\text{CH}_3\text{-CF}_3$, R143a) which has the highest dipole moment in the group of ethane-derived hydrofluorocarbons (HFCs). The automated high-temperature torsional quartz vibrator viscometer [3] was used at temperatures from 300 to 440 K with pressures to 68 MPa. For R143a, this range includes subcritical vapor and compressed liquid as well as supercritical states. In the literature, only a few viscosity data are available for this fluid and no measurements have been reported across the entire fluid region. R143a was also measured because of its potential use in supercritical extraction. Compared with other ethane-derived hydrofluorocarbons, R143a has a low critical temperature ($T_c = 345.857$ K) and a low critical pressure ($P_c = 3.761$ MPa) [6]. The combination of low critical point and high polarity, as well as its chemical stability, qualify R143a as a favorable supercritical solvent. The low critical point of pure R143a limits its use as a refrigerant. However, it is used in mixtures with other HFCs as a property modifier to blend efficient working fluids for vapor compression (Rankine) cycles [5]. Accurate pure fluid information is needed to model or predict the properties of such mixtures.

This report continues with considerations of the molecular size, shape, and charge distribution of R143a and their consequences for the unique properties of this compound. The purity of the sample is also addressed. The viscometer is described here in greater detail than in previous papers from this laboratory to explain the more accurate analysis of the measurement results that has been applied in this work. The effect of this more refined approach is reflected in the final comparison of the results with literature data for the viscosity of R143a.

2. Sample

2.1 Molecular Considerations

Macroscopic thermophysical properties are a reflection of molecular size, shape, charge distribution, and polarizability. In the series of fluorinated ethanes, trifluoroethane is the middle compound between ethane (C_2H_6) and perfluoroethane (C_2F_6). There are two isomers, 1,1,1-trifluoroethane ($\text{CF}_3\text{-CH}_3$, R143a) and 1,1,2-trifluoroethane ($\text{CHF}_2\text{-CH}_2\text{F}$, R143), both of which have unique properties among the fluorinated ethanes. A convenient way to illustrate these unique properties is to compare the lengths of the vapor pressure curves (the differences between critical temperatures and triple point temperatures $T_c - T_t$). This length is indicative of the magnitude of the attractive forces between the molecules [7]. If particles interact only with repulsive forces no liquid phase can be formed [8–12]. Thus, the shorter the vapor pressure curve, the more repulsive the interactions between molecules.

The lengths of the vapor pressure curves of the fluorinated ethanes in Fig. 1 show an increase from the nonpolar ethane (214.98 K) to the polar ethyl fluoride ($\text{CH}_3\text{-CH}_2\text{F}$, R161, 245.36 K) because of dipolar attractions between the latter molecules. This effect continues to the two difluoroethane isomers $\text{CHF}_2\text{-CH}_3$ (231.85 K, R152a) and $\text{CH}_2\text{F-CH}_2\text{F}$ (211.65 K, R152). However, the lengths of the vapor pressure curves of the trifluoroethanes differ

significantly. That of 1,1,1-trifluoroethane (R143a) drops to 184.517 K while that of the more symmetrical isomer 1,1,2-trifluoroethane (R143) increases to 240.75 K, the second highest of all fluorinated ethanes. This difference of the lengths of the vapor pressure curves indicates a significant decrease in intermolecular attractions in 1,1,1-trifluoroethane whereas the move of one fluorine atom to the second carbon results in a strong increase of attractions in 1,1,2-trifluoroethane. The increase of attractions arises from the higher number of connectivities through H...F halogen bonds [13–16] to form a denser network structure between these molecules than between the more asymmetrical isomer 1,1,1-trifluoroethane. In R143a, the fluorine atoms are concentrated on one carbon and this CF₃-group is very repulsive because of the electronegativity of fluorine. Separating the three fluorine and the three hydrogen atoms on the two carbon atoms results in the most polar fluorinated ethane, the “Janus molecule” 1,1,1-trifluoroethane. Its gas phase dipole moment was determined by Meyer and Morrison [17] as $\mu = (2.340 \pm 0.010)$ D (water: 1.8 D) while Gurova et al. determined an apparent dipole moment in the liquid phase of $\mu^* = 3.293$ D [18]. Properties of perfluoroalkylalkanes, of which R143a is the simplest, have been investigated by Morgado et al. [19, 20]. Rovigatti et al. found recently *in silico* unconventional thermodynamic phase behavior exhibited by Janus patchy particles [21].

Continuing in the series of fluorinated ethane derivatives, the lengths of the vapor pressure curves of the tetrafluoroethanes, 204.36 K for the more asymmetrically fluorinated 1,1,1,2-tetrafluoroethane (R134a) and 207.59 K for the isomer 1,1,2,2-tetrafluoroethane (R134) are both higher than that of R143a and differ less than those of the trifluoroethanes because both molecules have partial polar sites that can network via H...F halogen bonds. However, with the CF₃-group in R134a as a center of repulsion, the length of the vapor pressure curve of this compound is shorter than that of its isomer where the fluorine atoms are distributed over both carbon atoms. This trend continues with pentafluoroethane, the vapor pressure curve length of which decreases to 166.81 K, and eventually to perfluoroethane with the shortest vapor pressure curve of only 119.93 K. Note that this is lower than even that of ethane. This is just one of the many peculiar properties of perfluorinated compounds [22] all of which arise from fluorine being the most electronegative element with a very low polarizability of its electron cloud. This stiffness leads to stronger repulsions between perfluorinated compounds than between their perhydrogenated counterparts which is reflected in shorter vapor pressure curves.

Our assessment is based on similar observations that we made with the viscosities of fluorinated propane isomers [23, 24] and two fluorinated propene isomers [25] as well as a wealth of yet to be published viscosity measurements of fluorinated ethanes in binary and ternary mixtures.

To support and illustrate the preceding discussion of molecular aspects, Figure 2 shows four views of the size, shape, and charge distribution of 1,1,1-trifluoroethane. They are based on *ab initio* calculations that were performed in this study with density functional theory at the B3LYP level and with the 6-311++G** basis set [26]. The electrostatic potential is color-mapped onto an electron density isosurface at a value of 0.002 electrons·au⁻³ (with 1 atomic unit = 0.05292 nm being the Bohr radius of hydrogen). This surface encloses more than 99 % of the molecule. While the main objective of the *ab initio* calculations was the

visualization of the molecule, we mention that the area of the electron density isosurface was calculated as $89.47 \text{ \AA}^2$, the volume enclosed by it as $67.56 \text{ \AA}^3$, and the gas phase dipole moment was obtained as 2.58 D, which is 10 % higher than the previously quoted experimental value [17] because of the approximations used in the calculations. The color scale of Fig. 2 represents the electrostatic potential ranging from red (negative charge, $-76.3 \text{ kJ}\cdot\text{mol}^{-1}$) to blue (positive charge, $124.6 \text{ kJ}\cdot\text{mol}^{-1}$). This representation of the charge distribution in R143a illustrates the very dipolar character of the molecule. Dots on the electron density isosurface indicate those parts of the surface that are inaccessible by other molecules of the same species.

2.2 Sample Preparation and Purity

The sample fluid was obtained from a commercial source. Sample from the vapor space of the supply cylinder was condensed into a stainless steel cylinder with a volume of 300 cm^3 that had been evacuated to $1.3 \times 10^{-5} \text{ Pa}$. The sample cylinder was then fully immersed into liquid nitrogen until its content was frozen. Vacuum was pumped on the sample cylinder for 30 minutes. Then, it was returned to room temperature to melt its contents. This freezing and pumping cycle was repeated two more times to degas the sample. Subsequently, the vapor phase from the sample cylinder was analyzed by a gas chromatographic-mass spectrometric method. The sample purity was determined as 99.93% R143a with a 0.04 % impurity being consistent with 1,2-difluoropropane and 0.03 % air [5].

The dielectric properties of the sample were probed *in situ* in the torsional quartz vibrator viscometer. Details will be given after the following discussion of the transducer, the measurement set up, and the measurement procedure.

3. Viscometer

The torsional quartz vibrator viscometer (TQV) belongs to the class of sensors where the viscosity of a gas or liquid is deduced from the damping that it exercises on a vibrating element. Figure 3a illustrates the transducer used in this work where the right circular piezoelectric quartz cylinder is mounted in the center of four brass electrodes, which are pairwise connected and one pair of which emits an alternating electric field due to an applied ac drive voltage of variable frequency. The cross-section in Figure 3b is adapted from [4] and indicates conceptually the electric field lines from the electrodes through the annular fluid layer and the quartz cylinder to illustrate how the sample is exposed to the alternating electric field. A complete analysis of the deformation of the quartz cylinder that results from the electric field and the dielectric properties of the sample has yet to be performed.

The unique feature of the torsional quartz vibrator sensor compared with other vibrating viscometers is that the quartz cylinder deforms predominantly torsionally as indicated in Figure 3c, thus ideally only shearing the sample fluid without displacing it normally to the surface of the cylinder. Consequently, damping of the vibration due to the inertia of the fluid is avoided. The damping due to shearing of the fluid is obtained by measuring the response of the vibrator near the resonant frequency (forced mode) or by monitoring the decay of its free vibration over time (free mode, [27, 28]). Both methods require measurements in both the fluid and in vacuum. All measurements reported here were carried out in the forced

mode. The working equation of the instrument gives the product (dynamic viscosity $\eta \times$ density ρ). It was derived by Webeler [29] and reads

$$\eta \times \rho = \left(\frac{m}{S_{Tp}} \right)^2 (\pi f^*) \left(\frac{\Delta f}{f^*} - \frac{\Delta f_0}{f_0^*} \right)^2. \quad (1)$$

The ability to determine the surface area S_{Tp} of the quartz cylinder with sufficient accuracy makes the TQV an absolute instrument which does not require calibration with a viscosity standard. Subscripts Tp indicate that S varies with temperature and pressure due to the thermal expansion of the quartz cylinder and due to the compression by the fluid. The densities of R143a to obtain the viscosities from eq. (1) were calculated from the *International Standard Formulation for the Thermodynamic Properties of 1,1,1-Trifluoroethane (HFC-143a)* by Lemmon and Jacobsen [6] as implemented in NIST Standard Reference Database 23 REFPROP, version 9.1 [30]. Their uncertainty is reported as 0.1 %. The other quantities in eq. (1) are discussed in the following sections.

3.1 Vibrator Geometry

On the right hand side of eq. (1) are the mass m of the cylindrical quartz rod and its surface area S_{Tp} , calculated from its measured length L and diameter D with appropriate account for thermal expansion and compression by the fluid. The quartz rod in the present measurements was the unswept specimen D that was used in earlier investigations [3, 5, 31]. Unswept means that the quartz crystal was not further purified after it was grown and cut [32]. Its mass was measured as $m = (0.96620 \pm 0.0001)$ g which leads to a negligible uncertainty in m^2 in eq. (1). The rod's length was determined at a room temperature of 22 °C as $L = 50.076$ mm, and its average diameter as $D = 3.0460$ mm. The uncertainty of the length measurements was $2.54 \cdot 10^{-6}$ m which results in an uncertainty of 0.2 % in the square of the surface area S_{Tp}^2 in eq. (1).

Figure 3a illustrates the orientations of the quartz crystal's axes which are mentioned in the following discussion. Due to the X-cut of the specimen relative to the quartz crystal lattice, the resonator deforms anisotropically under the influence of temperature and pressure. The functions that have been applied in this laboratory to correct for the anisotropic deformation of the quartz cylinder are documented below [1, 2]. The relative fractional thermal expansion in direction of the optic axis (z -axis) is accounted for by

$$\left(\frac{\Delta l}{l} \right)_{z,T} = 0.998821 - 3.7100 \cdot 10^{-7} T + 1.8794 \cdot 10^{-8} T^2 - 1.2907 \cdot 10^{-11} T^3, \quad (2)$$

with the temperature T in kelvin, while thermal expansion in direction of the x (electric) and y axes is accounted for by

$$\left(\frac{\Delta l}{l}\right)_{xy,T} = 0.994799 + 2.9369 \cdot 10^{-5}T - 5.9583 \cdot 10^{-8}T^2 + 6.80 \cdot 10^{-11}T^3, \quad (3)$$

The relative fractional deformation due to pressure p in megapascals in direction of the optic axis (z -axis) is given by

$$\left(\frac{\Delta l}{l}\right)_{z,p} = 1 - 8.5862 \cdot 10^{-6} p, \quad (4)$$

and in direction of the x (electric) and y axes by

$$\left(\frac{\Delta l}{l}\right)_{xy,p} = 1 - 6.6124 \cdot 10^{-6} p. \quad (5)$$

The surface area of the elliptic cylinder S_{Tp} is calculated with the temperature and pressure dependent semiaxes and the length of the quartz crystal

$$r_{z,Tp} = \frac{D}{2} \left(\frac{\Delta l}{l}\right)_{z,T}, \left(\frac{\Delta l}{l}\right)_{z,p}, r_{y,Tp} = \frac{D}{2} \left(\frac{\Delta l}{l}\right)_{xy,T}, \left(\frac{\Delta l}{l}\right)_{xy,p}, \text{ and } L_{x,Tp} = L \left(\frac{\Delta l}{l}\right)_{xy,T}, \left(\frac{\Delta l}{l}\right)_{xy,p}, \quad (6)$$

from the approximate formula

$$S_{Tp} = 2\pi \left(r_{z,Tp} r_{y,Tp} + L_{x,Tp} \sqrt{\frac{r_{z,Tp}^2 + r_{y,Tp}^2}{2}} \right), \quad (7)$$

Accounting for thermal expansion results in a maximum increase in the square of the surface area S_{Tp}^2 in eq. (1) of 0.71 % at 440 K, the highest temperature measured in the present investigation. Compression of the quartz crystal due to fluid pressure results in a maximum decrease of the surface area S_{Tp}^2 in eq. (1) of -0.19 % at 68 MPa, the highest pressure measured in the present investigation.

3.2 Resonance Measurements and Analysis

The remaining symbols on the right hand side of eq. (1) denote resonant frequencies of the quartz rod f^* in the fluid and in vacuum (subscript 0) and the associated bandwidths Δf and Δf_0 of the resonance curves. These four quantities are essential for the viscosity determination and shall be discussed in more detail. They are obtained by scanning the complex electrical admittance, $Y = G + jB$, through the resonance of the quartz rod. The real part G is the conductance and the imaginary part B is the susceptance. Two examples of such scans are shown in Figure 4. They represent the lowest and the highest viscosity of R143a to indicate the ranges over which f^* and Δf varied for this fluid: f^* from 39541.1741 Hz to 39474.4303 Hz and Δf from 0.5272 Hz to 31.325 Hz.

One of the key improvements that we introduced in the torsional quartz vibrator viscometer is the detailed resolution of the influence of the AC drive voltage on the measured viscosity which has not been documented before for such transducers. Particularly important for absolute viscosity measurements is the accurate determination of the internal damping of the transducer in vacuum, represented by the resonant frequency f_0^* and the bandwidth Δf_0 . Their dependence on temperature and drive voltage was measured systematically in a vacuum of 1.3×10^{-5} Pa from approximately 300 K to 460 K and at drive voltage levels from 5 mV to 1.1 V. Due to the high sensitivity of the vibrator in vacuum, the frequency scanning had to be modified by observing ring-down time intervals t_f after each frequency step until the vibration of the quartz cylinder had become stationary at the new frequency and the admittance could be recorded. While these ring-down time intervals needed to be as long as 270 s at 76 K in our low-temperature instrument [28], durations of up to 30 s were required at 5 mV drive voltage in the high-temperature instrument that was used in the present study. The wait time intervals t_f in vacuum could be reduced with increasing temperature and drive voltage. However, intervals of up to 20 s were also necessary for measurements in gases and minimum intervals of 3 s were applied even up to the highest pressures in liquids for improved repeatability of the measurements.

Figure 5 shows the measured bandwidths in vacuum Δf_0 vs. temperature. An increase with drive voltage and, more pronounced, with temperature is observed. The smallest bandwidths Δf_0 were measured at 5 mV drive voltage with a minimum of 0.075 Hz at approx. 307 K. An increase of the drive voltage to 0.1 V increases Δf_0 to 0.09 Hz at that temperature, whereas a further increase to 1.1 V results in a doubling of Δf_0 to 0.18 Hz. In fact, the small increase of Δf_0 between 5 mV and 0.1 V compared with the increase from 0.1 V to 1.1 V was observed at all measured temperatures. The vacuum bandwidths increase also with temperature although slowly up to 370 K but with an exponential increase developing above that temperature. In the elevated temperature range, the influence of the drive voltage on Δf_0 becomes smaller and smaller indicating a loss of piezoelectric sensitivity of the unswept quartz rod. Anticipating the viscosity results for R143a discussed below it is worthwhile to note here that the upper temperature limit for accurate viscosity measurements with this quartz cylinder turned out to be 420 K. The results in Fig. 5 explain this finding because there is no drive voltage dependence of Δf_0 above this temperature anymore.

The measured temperature dependence of the resonant frequency in vacuum $f_0^*(T)$ is not shown here because it exhibited a negligible dependence on the drive voltage. It conformed with the well established characteristics for static resonators [33] and could be represented by a quadratic polynomial with a resonant frequency maximum of 39.546 kHz at 369 K.

The bandwidth of the quartz vibrator's resonance in vacuum f_0 represents predominantly the damping of the quartz rod's vibration due to its internal friction against torsional displacement but also due to losses in its suspension in the transducer. Obviously, the sensitivity of the sensor to the viscosity measurement can be increased by reducing the vacuum bandwidth f_0 as much as possible which would be accomplished by measuring f_0 always at the lowest possible drive voltage (5 mV with our instrumentation). Due to resolution limits of the impedance analyzer this was not possible throughout the entire temperature range. Therefore, vacuum bandwidths $f_0(T)$ and resonant frequencies $f_0^*(T)$ determined at the drive voltage level 0.1 V were used in the analysis of the viscosity measurements via the working eq. (1).

Ideally, measurements with the TQV should be guided by considering the amplitude of the torsional displacement of the quartz rod in the fluid and in vacuum. As we noted previously, this can be accomplished by measuring the free decay of the quartz's vibration [28] where the amplitude of the torsional displacement of the sensor is monitored directly. Forced mode measurements provide no direct information about the rod's angular displacement. Figure 6 illustrates that the same drive voltage U_{osc} causes a larger torsional displacement in vacuum δ_0 than in a fluid δ when the shear of the fluid acts against the torsional piezoelectric deformation of the quartz rod due to the electric field. Conversely, the torsional displacement δ that is caused by a certain drive voltage $U_{osc,f}$ in a fluid of viscosity η may involve a displacement in vacuum δ_0 that a different, lower drive voltage $U_{osc,0}$ would cause. The torsional displacements are represented in eq. (1) by the bandwidths. Consequently, subtracting in eq. (1) $(\Delta f_0/f_0^*)$ from (f/f_0^*) both determined at the same voltage will result in systematically too low viscosities because the internal damping of the sensor is overcompensated. As an example, the magnitude of this systematic error is shown in Figure 7 for R143a along the supercritical 400 K-isotherm with five drive voltages from 0.1 V to 1.1 V. Measurements in the fluid were evaluated with the resonance frequencies and bandwidths in vacuum measured with the same drive voltage. A supercritical isotherm is selected because it illustrates the effect across all states from compressed fluid to dilute gas. The drive voltage dependence of the viscosities is shown in terms of percent deviations of the results of eq. (1) for each drive voltage relative to viscosities of R143a predicted with the extended corresponding states model as implemented in NIST Standard Reference Properties System REFPROP, version 9.1 [30]. The spread of the percent deviations is smallest at the highest densities ($1000 \text{ kg}\cdot\text{m}^{-3}$) and amounts to about 5 % that the results with drive voltage 1.1 V are lower than the results measured with drive voltage 0.1 V. The latter agree best with the calculated viscosities for all densities along the isotherm. The 5 % band of viscosity variations with drive voltage continues unchanged to lower densities but begins to increase below $350 \text{ kg}\cdot\text{m}^{-3}$. The spread widens strongly below $200 \text{ kg}\cdot\text{m}^{-3}$ with particular decreases of the results for the drive voltages 0.6 V and 1.1 V. These decreases in the obtained fluid's viscosity reflect the increased mismatch between the torsional

displacements with and without external damping when the bandwidths are evaluated at the same drive voltage. At the lowest density, the results with drive voltages 0.6 V and 1.1 V are about 25 % and 28 % lower than the reference values. The discrepancies decrease with decreasing drive voltage to -1.7 % at 0.1 V at that density.

As a result of such analyses for all temperatures that were measured in this study it was concluded that the mismatch of the torsional displacement in fluid and in vacuum is smallest for the drive voltage 0.1 V up to and including 400 K while results at 0.2 V were considered more accurate at 420 K due to the rapidly decreasing sensitivity of the unswept quartz crystal above 400 K. These analyses make it also clear that the uncertainty of viscosity measurements with torsional quartz vibrators can be significantly reduced further by applying drive voltages below 0.1 V and extrapolating the drive voltage dependence of f_0 and f to zero drive voltage. With the instrumentation used in this work this was not possible without loss of resolution in the admittance measurement. All data reported here are averages of four experimental repetitions. The deviations of the raw data in Fig. 7 show that the repeatability of the measurements was typically within 0.5 %.

At 39 kHz, which is far away from the resonances, the measured admittance Y_{∞} characterizes electric properties of the fluid. The electrical conductivity is represented by the real part, G_{∞} , while the dielectric permittivity can be obtained from the imaginary part B_{∞} . The measured conductances for R143a are shown in Figure 8. The increase of G_{∞} above $\rho = 400 \text{ kg}\cdot\text{m}^{-3}$ is systematic but still under $1 \text{ }\mu\text{S}$ and did not reach a magnitude where the observed viscosity would need to be corrected for electro-viscous effects in the sample [34]. We base this assessment on the molecular considerations in section 2.1, on our published direct comparisons of viscosity measurements with and without exposure to an electric field [5], and on a much larger body of experiences that has not yet been published including fluids such as difluoromethane (R32) with conductances up to 100 times that of R143a.

The estimated uncertainty of the present measurement results remains therefore as before at 2% at a 95 % confidence level ($k = 2$). The standard uncertainty of the temperature measurements with an SPRT is $u_T = 20 \text{ mK}$. Pressures were measured with two transducers both with a standard uncertainty of 0.01 % of full scale as stated by the manufacturer. The high-pressure transducer had an upper limit of 68 MPa and the low-pressure transducer was used up to pressures of 0.68 MPa.

4. Results

The viscosity of R143a was measured in this study at eight sub- and supercritical temperatures from 300 K to 440 K with pressures up to 68 MPa. The experimental results up to 421 K are reported in Table 1 together with standard deviations of the measured pressures, temperatures, and viscosities to indicate their Type A uncertainties [35]. The results at 440.5 K are displayed in Figures 9 and 10 to document their elevated systematic uncertainties, but they are not tabulated to prevent their erroneous use in data collections. Measured pressures and temperatures were converted to densities with the fundamental equation of state of Lemmon and Jacobsen [6] as implemented in NIST Standard Reference Database REFPROP [30]. These are also reported in Table 1 as are viscosities estimated with the

extended corresponding states model for the viscosity of R143a of Huber et al. [36] as implemented in REFPROP. These estimated viscosities served as benchmarks to identify trends in the present results and for comparison with literature data.

Previously, only two other laboratories determined the viscosity of R143a away from the saturation line. Takahashi et al. [37] measured with an oscillating disk viscometer in the gas region from 298.15 K to 423.15 K with pressures up to the vapor pressure or the extrapolated vapor pressure curve at temperatures above the critical temperature of $T_c = 345.857$ K [6]. The expanded uncertainty of these results was reported as 0.3 % or less. The second data set was obtained by Avelino et al. [38] with a vibrating wire viscometer in the compressed liquid region at temperatures between 254.35 K and 293.17 K with pressures from 1.24 MPa to 10.07 MPa. The uncertainty of these results was reported as less than 1 %. The contribution of the present work to an improved knowledge of the viscosity of R143a is illustrated in Figure 9 by comparison with these two data sets. The large data gap between $367 \text{ kg}\cdot\text{m}^{-3}$ and $953 \text{ kg}\cdot\text{m}^{-3}$ has been closed. No significant temperature dependence of the viscosity can be discerned above $700 \text{ kg}\cdot\text{m}^{-3}$.

Figure 9 indicates systematic deviations of the present results at 440.5 K towards low densities. To discern these and other deviations of the present results at higher resolution, Figure 10 shows their percent deviations from the benchmark viscosities as a function of density. Temperature dependences can be discerned from the individually marked isotherms. The margins of the estimated uncertainty of 2 % are indicated by horizontal lines in the diagram. Most evident are systematic deviations at nearly all temperatures in the gas region at densities below $220 \text{ kg}\cdot\text{m}^{-3}$. The deviations of the results at 440.5 K increase up to 26.6 % at $2.3 \text{ kg}\cdot\text{m}^{-3}$. Deviations of such order of magnitude may be caused by two effects. One of them is obviously inadequate accounting for the background damping f_0 of the vibrator in vacuum with the resonance measurement technique and with the equipment that was available in this study. Of broader influence is the fading piezoelectric sensitivity of the unswept quartz at temperatures above 420 K as shown in Figure 5. Consistent with that fading sensitivity is the trend of the deviations in Figure 10 at 440.5 K and densities above $220 \text{ kg}\cdot\text{m}^{-3}$. They are systematically below the uncertainty margin of -2 % whereas all other results of the present study are within the margin band of 2 %. From these observations we deduce that viscosity measurements with unswept quartz vibrators are reliable only up to a temperature of 420 K. Therefore, the results of the present measurements at 440.5 K are only shown in Figures 9 and 10 but not reported in Table 1.

5. Comparison with Literature Data

The comparison of the present results against benchmark viscosities calculated with an extended corresponding states model indicates systematic deviations below $220 \text{ kg}\cdot\text{m}^{-3}$ and agreement within the estimated uncertainty of 2 % at all higher densities. A more rigorous reliability test of the present results is their comparison with literature data. Besides the aforementioned measurement results of Takahashi et al. [37] and of Avelino et al. [38] two other data sets were included in this comparison because they were obtained with even different techniques. The data of Ripple and Defibaugh [39] were determined with a sealed gravitational capillary viscometer where saturated liquid and vapor are in phase equilibrium.

Therefore, the efflux of the liquid is subject to the buoyancy of the vapor which has to be taken into account when calculating viscosities from the measured efflux times, especially at increased temperatures. Ripple and Defibaugh [39] were the first to point out in their paper that this vapor buoyancy correction had not been applied in some earlier measurements with such sealed viscometers in the literature resulting in systematic viscosity deviations of up to 14 %. Therefore, the data of Ripple and Defibaugh are of reference quality even though they reported a total expanded uncertainty of 2.4 % for their measurements. Another reference quality of their measurements for the results of the present study is that the highly polar R143a was not exposed to an electric field in their capillary viscometer whereas it was in the torsional vibrator viscometer used in this study.

This aspect applies also to the viscosities which Fröba et al. published in 2000 for R143a in the temperature range 253.15 K to 333.15 K. They were determined from the surface light scattering (SLS) at the gas-liquid interface between saturated vapor and liquid [40]. A maximum uncertainty of 4 % was quoted for these data. A subsequent paper by Fröba et al. [41] reported the same viscosity data and reiterated the four-parameter correlation of the results in the previous publication [40]. However, in his dissertation Fröba [42] reported re-analyzed values for the viscosity data of nine pure fluids and three binary mixtures that had been published in journal articles before.

Percent deviations of the present results and of those from the literature are compared in Figure 11 with the benchmark viscosities vs. density. The trend of increasing deviations of the present results in the gas region at decreasing densities below $220 \text{ kg}\cdot\text{m}^{-3}$ occurs also in the deviations of the results of Takahashi et al. [37], which cover a comparable temperature range from 298.15 to 423.15 K, albeit less pronounced. At the lowest densities their deviations range between 1.1 % and 3.3 % which both exceed their estimated uncertainty of 0.3 %. This means that the reference viscosities are by about 2 % too low in the limit of zero density. On the other hand, the present results scatter at the lowest densities from -6.7 % to 8.3 % with their bulk between 1 % and 8.3 %. The highest systematic deviations occur in the subcritical vapor measurements below $100 \text{ kg}\cdot\text{m}^{-3}$ at 302, 320, and 341 K but the data on the supercritical isotherms 361, 380.6, 401, and 421 K are rather consistent with those of Takahashi et al. [37], apart from two outliers at very low density at 380.6 K. In the density range from $100 \text{ kg}\cdot\text{m}^{-3}$ to $220 \text{ kg}\cdot\text{m}^{-3}$ the deviations of the data by Takahashi et al. [37] are systematic with temperature which is also reflected by the deviations of the present data. Four points of Takahashi et al. [37] at 348.15 K with deviations of 3.3 % may appear as outliers but they are part of this temperature systematic because they are closely met by present results at 341 K with deviations between 3.3 and 3.6 %. Again, this is an indication that the benchmark viscosity model has an incorrect temperature dependence in that region.

At densities above $220 \text{ kg}\cdot\text{m}^{-3}$ the deviations of the present viscosity results from the benchmark data are all within the uncertainty band of 2 %. Their closest agreement with the literature data is seen in the compressed liquid region with the results of Avelino et al. [38] which are also the most accurate with an estimated expanded uncertainty of 1 %. The present results agree with those of Avelino et al. within this margin. The deviations of the results of Ripple and Defibaugh [39] show an almost constant offset between -1 % and -1.5 % which indicates that they were used to determine the shape factors in the extended

corresponding states model with which the benchmark viscosities were calculated. The results of Ripple and Defibaugh [39] agree with the present results within their estimated uncertainty of 2 % which is smaller than the total expanded uncertainty of 2.4 % of the results of Ripple and Defibaugh [39]. Deviations in a range from –7.3 % to 2.3 % exist between the journal-published data of Fröba et al. [40, 41] and the benchmark viscosities. This exceeds their estimated uncertainty of 4 %. However, the re-analyzed values in the dissertation of Fröba [42] with the same quoted uncertainty of 4 % deviate only between –1.9 % and 0.9 %.

It is rare that viscosity measurement results from four different techniques agree as closely as found here. More important is the consistent agreement of the results from the torsional quartz vibrator viscometer with the results from the other techniques. Earlier NIST measurements with this type of viscometer turned out to deviate from literature data often by more than 2 % and in systematic ways [43–45]. This paper provides further evidence that a measurement uncertainty of 2 % can be sustainably achieved with this viscometric technique even with highly polar fluids.

7. Concluding Remarks

New viscosity measurements were performed with a torsional quartz vibrator viscometer on the highly polar hydrofluorocarbon 1,1,1-trifluoroethane ($\text{CH}_3\text{--CF}_3$, R143a). The reported data cover a temperature range from 300 K to 420 K with pressures to 68 MPa. This includes fluid states from the very dilute gas to the compressed liquid. Measurements at supercritical temperatures of this compound were conducted for the first time.

The results of the new measurements are remarkable in several respects. Their agreement with literature data from three other viscometric techniques in the saturated and compressed liquid region is the closest that has been achieved with this technique since the argon measurements of Haynes [2]. However, here the technique was employed with improved accounting for the torsional displacement of the sensor in vacuum and in fluid. With further improvements of the instrument theory and design it should be possible to reduce the uncertainty of this viscometric technique to 1 % or less for measurements of liquids.

Secondly, the close agreement was achieved with the highly polar fluid 1,1,1-trifluoroethane. This is remarkable because it was thought in the past that the torsional quartz vibrator technique would give rise to electroviscous contributions in addition to the Newtonian viscosity as the sample fluid is exposed to the alternating electrical field that drives the torsional vibration and to the alternating charge on the surface of the piezoelectric quartz cylinder. The present results corroborate our previous findings [5] that such electroviscous contributions are negligible as long as the conductance of the sample is less than 1 μS . This significantly expands the range of fluids which can be measured with the torsional quartz vibrator technique.

Thirdly, this study shows again the remarkably wide viscosity range that can be probed with this sensor. Most other viscometric techniques are subject to range limitations because of geometry constraints on the fluid dynamics. Examples are the diameters of capillary

instruments, of falling body sensors, or of the wires in vibrating wire viscometers that need to be changed with viscosity to maintain laminar flow. The surface light scattering technique is limited to saturated liquids. Here, the torsional quartz vibrator was used over a range where the viscosity varied by a factor of 24 down to very dilute gas states where the measurement uncertainty depends increasingly on the correct background damping of the vibrator in vacuum. Direct comparison with results from a fourth technique, an oscillating disk viscometer, show a remarkable consistency of the results of the torsional quartz vibrator. With higher resolution instrumentation at lower drive voltages or by measuring the torsional displacement directly in the time domain, it should be possible to reduce the uncertainty of measurements at densities from $150 \text{ kg}\cdot\text{m}^{-3}$ to $30 \text{ kg}\cdot\text{m}^{-3}$ to 1.5 % or less.

Finally, considered over the entire density range, the results of the present study indicate systematic deviations from the calculated viscosities in an oscillatory pattern which are likely due to the density terms in the extended corresponding states model. Thus, the present results will be valuable to formulate a new density function that represents the reference fluid's viscosity more accurately.

Acknowledgments

R. F. Hafer was supported by the National Institute of Standards and Technology Professional Research Experience Program (PREP) and by a travel grant from the National Science Foundation. Partial funding of this research was provided by the U. S. Dept. of Energy, Office of Building Technologies, under contract DE-AI01-91CE23808, through grant number DE-FG02-91CE23810 (Materials Compatibility and Lubricants Research (MCLR) on CFC-Refrigerant Substitutes) via the Air Conditioning and Refrigeration Technology Institute (ARTI), and through contract number 665-50800 (Thermophysical Properties). Dr. T. J. Bruno (NIST Boulder) performed sample analyses. A. L. is grateful to Prof. A. Fröba for providing him with a copy of his dissertation. Dr. Robert F. Berg (NIST) and an anonymous colleague as journal referee are acknowledged for their helpful reviews that made the paper stronger.

References

1. Diller DE. Measurements of the viscosity of parahydrogen. *J Chem Phys.* 1965; 42:2089–2100.
2. Haynes WM. Viscosity of Gaseous and Liquid Argon. *Physica.* 1973; 67:440–470.
3. Diller DE, Frederick NV. Torsional piezoelectric crystal viscometer for compressed gases and liquids. *Int J Thermophys.* 1989; 10:145–157.
4. Meier, K. Observation and Modeling of Polar Fluid Behavior in a Torsionally Oscillating Crystal Viscometer. Universität Hannover, FRG, and National Institute of Standards and Technology; Boulder, Colorado: 1994.
5. Laesecke A. Viscosity Measurements and Model Comparisons for the Refrigerant Blends R-410A and R-507A. *ASHRAE Trans Symp.* 2004; 110(part 2):503–521.
6. Lemmon EW, Jacobsen RT. An International Standard Formulation for the Thermodynamic Properties of 1,1,1-Trifluoroethane (HFC-143a) for Temperatures from 161 to 450 K and Pressures to 50 MPa. *J Phys Chem Ref Data.* 2000; 29:521–552.
7. Laesecke A, Muzny CD. Reference Correlation for the Viscosity of Carbon Dioxide. *J Phys Chem Ref Data.* 2017; 46:013107. [PubMed: 28736460]
8. Widom B. Intermolecular forces and the nature of the liquid state. *Science.* 1967; 157:375–382. [PubMed: 17798690]
9. Anderson VJ, Lekkerkerker HNW. Insights into phase transition kinetics from colloid science. *Nature.* 2002; 416:811–815. [PubMed: 11976674]
10. Mulero, A. *Lect Notes Phys.* Springer-Verlag; Berlin, Heidelberg, New York: 2008. Theory and Simulation of Hard-Sphere Fluids and Related Systems.

11. Larsen RJ, Zukoski CF. Effect of the range of repulsions on the existence of a stable liquid phase. *J Chem Phys.* 2012; 136:054901. [PubMed: 22320758]
12. Fuentes-Herrera M, Moreno-Razo JA, Guzmán O, López-Lemus J, Ibarra-Tandi B. Separating the effects of repulsive and attractive forces on the phase diagram, interfacial, and critical properties of simple fluids. *J Chem Phys.* 2016; 144:214502. [PubMed: 27276958]
13. Cabral BJC, Guedes RC, Pai-Panandiker RS, Nieto de Castro CA. Hydrogen bonding and the dipole moment of hydrofluorocarbons by density functional theory. *Phys Chem Chem Phys.* 2001; 3:4200–4207.
14. Santos FJV, Pai-Panandiker RS, de Castro CAN, Mardolcar UV. Dielectric properties of alternative refrigerants. *IEEE Trans Dielectr Electr Insul.* 2006; 13:503–511.
15. Desiraju GR, Ho PS, Kloo L, Legon AC, Marquardt R, Metrangolo P, Politzer P, Resnati G, Rissanen K. Definition of the halogen bond (IUPAC Recommendations 2013). *Pure Appl Chem.* 2013; 85:1711–1713.
16. Shahi A, Arunan E. Hydrogen bonding, halogen bonding and lithium bonding: an atoms in molecules and natural bond orbital perspective towards conservation of total bond order, inter- and intra-molecular bonding. *Phys Chem Chem Phys.* 2014; 16:22935–22952. [PubMed: 25127185]
17. Meyer CW, Morrison G. Dipole Moments of Seven Partially Halogenated Ethane Refrigerants. *J Phys Chem.* 1991; 95:3860–3866.
18. Gurova AN, Ribeiro APC, Nieto de Castro CA, Mardolcar UV. Dielectric properties of 1,1,1-trifluoroethane (HFC-143a) in the liquid phase. *Fluid Phase Equilib.* 2009; 275:152–158.
19. Morgado P, Laginhas CMC, Lewis JB, McCabe C, Martins LFG, Filipe EJM. Viscosity of Liquid Perfluoroalkanes and Perfluoroalkylalkane Surfactants. *J Phys Chem B.* 2011; 115:9130–9139. [PubMed: 21634410]
20. Morgado P, Das G, McCabe C, Filipe EJM. Vapor Pressure of Perfluoroalkylalkanes: The Role of the Dipole. *J Phys Chem B.* 2014; 119:1623–1632.
21. Rovigatti L, Bianco V, Tavares JM, Sciortino F. Communication: Re-entrant limits of stability of the liquid phase and the Speedy scenario in colloidal model systems. *J Chem Phys.* 2017; 146:041103. [PubMed: 28147524]
22. Sinitsin, EN., Mikhalevich, LA., Yankovskaja, OP., Gulezkaja, IF., Ivakin, VB., Muratov, GN., Ermakov, GV. *Experimental Data and Calculation Methods* (in Russ). Ural Publishing Company Nauka; Ekaterinburg, Russia: 1995. Thermophysical Properties of Liquid Fluorinated Compounds.
23. Laesecke A, Defibaugh DR. Viscosity of 1,1,1,2,3,3-Hexafluoropropane and 1,1,1,3,3,3-Hexafluoropropane at Saturated-Liquid Conditions from 262 K to 353 K. *J Chem Eng Data.* 1996; 41:59–62.
24. Laesecke A, Hafer RF. Viscosity of Fluorinated Propane Isomers. 2. Measurements of Three Compounds and Model Comparisons. *J Chem Eng Data.* 1998; 43:84–92.
25. Cousins DS, Laesecke A. Sealed Gravitational Capillary Viscometry of Dimethyl Ether and Two Next-Generation Refrigerants. *J Res Natl Inst Stand Technol.* 2012; 117:231–256. [PubMed: 26900526]
26. Hehre, WJ. *A Guide to Molecular Mechanics and Quantum Chemical Calculations*. Wavefunction, Inc; Irvine, CA: 2003.
27. Hafer, RF. *Torsional Crystal Viscometry: Wide-Ranging Resonance Measurements and Feasibility Study of Transient-Decay Measurements*. Dept. of Chem. Eng., University of Colorado; 1999.
28. Hafer RF, Laesecke A. Extension of the Torsional Crystal Viscometer to Measurements in the Time Domain. *Meas Sci Technol.* 2003; 14:663–673.
29. Webeler, RWH. *Viscosity x Density Measurements For Normal Liquid Hydrogen and Various Ortho-Para Mixtures*. University of Cincinnati; 1961.
30. Lemmon, EW., Huber, ML., McLinden, MO. *NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 9.1*. National Institute of Standards and Technology, Standard Reference Data Program; Gaithersburg, Maryland: 2013.
31. Diller DE, Peterson SM. Measurements of the Viscosities of Saturated and Compressed Fluid 1-Chloro-1,2,2,2-Tetrafluoroethane (R124) and Pentafluoroethane (R125) at Temperatures Between 120 and 420 K. *Int J Thermophys.* 1993; 14:55–66.

32. Gualtieri, JG. Sweeping Quartz Crystals. In: McAvoy, BR., editor. IEEE 1989 Ultrasonics Symposium, IEEE; Montréal, CA. 1989; p. 381-391.
33. Walls FL, Gagnepain JJ. Environmental sensitivities of quartz oscillators. Ultrasonics, Ferroelectrics, and Frequency Control, IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control. 1992; 39:241-249.
34. Mala GM, Li D, Dale JD. Heat transfer and fluid flow in microchannels. Int J Heat Mass Transfer. 1997; 40:3079-3088.
35. Taylor, BN., Kuyatt, CE. NIST Technical Note 1297. National Institute of Standards and Technology; Washington, D. C: 1994. Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results.
36. Huber ML, Laesecke A, Perkins RA. Model for the Viscosity and Thermal Conductivity of Refrigerants, Including a New Correlation for the Viscosity of R134a. Ind Eng Chem Res. 2003; 42:3163-3178.
37. Takahashi M, Shibasaki-Kitagawa N, Yokoyama C. Viscosity of Gaseous HFC-143a (1,1,1-trifluoroethane) Under High Pressures. Int J Thermophys. 1999; 20:435-443.
38. Avelino HMNT, Fareleira JMNA, Oliveira CMBP. Viscosity of Compressed Liquid 1,1,1-Trifluoroethane (HFC-143a) and Pentafluoroethane (HFC-125). J Chem Eng Data. 2006; 51:1672-1677.
39. Ripple D, Defibaugh D. Viscosity of the Saturated Liquid Phase of Three Fluorinated Ethanes: R152a, R143a, and R125. J Chem Eng Data. 1997; 42:360-364.
40. Fröba AP, Will S, Leipertz A. Saturated Liquid Viscosity and Surface Tension of Alternative Refrigerants. Int J Thermophys. 2000; 21:1225-1253.
41. Fröba AP, Will S, Leipertz A. Thermal Diffusivity and Sound Speed of the Refrigerant R143a (1,1,1-Trifluoroethane). Int J Thermophys. 2001; 22:1021-1034.
42. Fröba, AP. Dissertation. Friedrich-Alexander-Universität Erlangen-Nürnberg; Germany: 2002. Simultane Bestimmung von Viskosität und Oberflächenspannung transparenter Fluide mittels Oberflächenlichtstreuung.
43. Krauss R, Luettmer-Strathmann J, Sengers JV, Stephan K. Transport Properties of 1,1,1,2-Tetrafluoroethane (R134a). Int J Thermophys. 1993; 14:951-988.
44. Fenghour A, Wakeham WA, Vesovic V. The Viscosity of Carbon Dioxide. J Phys Chem Ref Data. 1998; 27:31-44.
45. Huber ML, Laesecke A. Correlation for the Viscosity of Pentafluoroethane (R125) from the Triple Point to 500 K with Pressures up to 60 MPa. Ind Eng Chem Res. 2006; 45:4447-4453.

Figure 1.

Lengths of vapor pressure curves of ethane (C_2H_6), its partially fluorinated derivatives and their isomers, and of perfluoroethane (C_2F_6). The ASHRAE refrigerant designations are shown as inset texts.

Figure 2. Molecular size, shape, and charge distribution of 1,1,1-trifluoroethane, CH₃-CF₃. The color scale represents the electrostatic potential ranging from red (negative charge, $-76.3 \text{ kJ}\cdot\text{mol}^{-1}$) to blue (positive charge, $124.6 \text{ kJ}\cdot\text{mol}^{-1}$). See text for more details.

Figure 3. Viscosity sensor. a) Assembly (adapted from [2]), b) Cross section with electric field lines (adapted from [4]), c) Torsional vibration mode.

Figure 4.
Resonance curves at the lowest (top) and the highest measured viscosity of R143a.

Figure 5. Vacuum bandwidth Δf_0 as function of temperature T and drive voltage U_{osc} for unswept quartz cylinder D.

Figure 6.

Illustration of the influence of the drive voltage U_{osc} on the torsional displacements of the quartz rod in fluid and in vacuum, δ and δ_0 , (left). The associated bandwidths of the resonances, f and f_0 , are shown at right. The vacuum values represent the internal damping of the quartz rod. The same drive voltage causes a significantly greater torsional displacement in vacuum, δ_0 , than when the quartz rod is shearing the fluid, δ . To avoid overcompensating the internal damping of the quartz rod, eq. (1) should be evaluated with vacuum bandwidths f_0 measured at lower drive voltages than the bandwidths in fluids f .

Figure 7.

Systematic of percent deviations from predicted values along the supercritical 400 K isotherm of R143a when the viscosity measurements are analyzed in eq. (1) with bandwidths f and f_0 at five different drive voltages. The lowest drive voltage at which the impedance analyzer could be used without loss of resolution was 0.1 V. Results at higher drive voltages are systematically lower due to overcompensation of the internal damping of the quartz rod, f_0 . Measurements in the fluid were evaluated with the resonance frequencies and bandwidths in vacuum measured with the same drive voltage.

Figure 8.
Conductances G_{∞} of R143a at 39 kHz as measured in the torsional quartz vibrator viscometer.

Figure 9.

Range of the present results for the viscosity of R143a compared to the previous measurements away from the vapor-liquid coexistence by Takahashi et al. [37] in the gas region and by Avelino et al. [38] in the compressed liquid region.

Figure 10.

Percent deviations of the present results from the extended corresponding states model for the viscosity of R143a of Huber et al. (2003) [36] as implemented in REFPROP.

Figure 11.

Percent deviations of the present results and of selected literature data from the extended corresponding states model for the viscosity of R143a of Huber et al. (2003) [36] as implemented in REFPROP.

Table 1

Experimental Viscosity Data of R143a Measured in this Work

Note: Values listed here are deemed to include only minor systematic uncertainties. To demonstrate the effects of systematic uncertainties in the performance of the transducer and in the theory of the instrument, more values are displayed in Figures 9 and 10 than are tabulated here. The symbol s denotes standard deviations of four consecutive measurements.

Pressure MPa	s_p MPa	s_p/p %	T_{90} K	s_T K	η mPa·s	s_η mPa·s	s_η/η %	ρ kg·m ⁻³	η mPa·s	$100(\eta_{\text{exp}} - \eta_{\text{calc}})$ %
exp	exp	exp	exp	exp	exp	exp	exp	calc	calc	
0.9018	0.00014	0.02%	302.60	0.005	0.01173	0.00001	0.08%	35.8329	0.01127	4.1
0.3932	0.00004	0.01%	302.30	0.014	0.01159	0.00002	0.18%	14.0590	0.01123	3.3
0.3082	0.00003	0.01%	302.29	0.016	0.01148	0.00008	0.70%	10.8516	0.01123	2.2
0.1461	0.00001	0.00%	302.21	0.015	0.01137	0.00002	0.14%	5.0038	0.01124	1.2
1.8164	0.00653	0.36%	320.04	0.046	0.01259	0.00042	3.33%	81.1361	0.01242	1.4
1.7052	0.00269	0.16%	320.00	0.023	0.01264	0.00040	3.18%	73.6987	0.01232	2.6
0.6218	0.00009	0.01%	320.05	0.010	0.01227	0.00003	0.23%	21.4587	0.01193	2.8
0.4595	0.00008	0.02%	319.95	0.013	0.01213	0.00001	0.09%	15.4733	0.01191	1.8
0.3155	0.00003	0.01%	319.96	0.003	0.01200	0.00001	0.09%	10.4030	0.01190	0.8
0.1504	0.00001	0.01%	319.93	0.003	0.01166	0.00002	0.16%	4.84719	0.01190	-2.0
0.7021	0.00008	0.01%	340.99	0.021	0.01305	0.00003	0.19%	22.5252	0.01275	2.4
0.7020	0.00009	0.01%	341.02	0.009	0.01303	0.00005	0.38%	22.5192	0.01275	2.2
0.6427	0.00009	0.01%	341.01	0.011	0.01304	0.00004	0.33%	20.4694	0.01274	2.3
0.5003	0.00004	0.01%	340.99	0.014	0.01300	0.00004	0.32%	15.6677	0.01271	2.3
0.3511	0.00004	0.01%	340.99	0.007	0.01297	0.00005	0.35%	10.8094	0.01269	2.2
0.2010	0.00001	0.01%	340.98	0.005	0.01310	0.00002	0.14%	6.08670	0.01268	3.3
0.1071	0.00003	0.03%	340.99	0.007	0.01272	0.00022	1.73%	3.21061	0.01267	0.4
67.5556	0.00555	0.01%	361.02	0.002	0.1793	0.00032	0.18%	1060.17	0.18043	-0.6
59.9099	0.00211	0.00%	361.02	0.004	0.1672	0.00029	0.17%	1041.59	0.16784	-0.4
52.2698	0.00242	0.00%	361.02	0.003	0.1551	0.00020	0.13%	1020.64	0.15528	-0.1
44.3024	0.00370	0.01%	361.02	0.004	0.1427	0.00007	0.05%	995.402	0.14203	0.5
37.5032	0.00292	0.01%	361.01	0.005	0.1322	0.00033	0.25%	970.110	0.13044	1.3

Pressure MPa	s_p MPa	s_p/p %	T_{90} K	s_T K	η mPa·s	s_η mPa·s	s/η %	ρ kg·m ⁻³	η calc	$100(\eta_{\text{exp}}/\eta_{\text{calc}} - 1)$ %
exp	exp	exp	exp	exp	exp	exp	exp	calc	calc	
31.8992	0.00130	0.00%	361.02	0.004	0.1218	0.00011	0.09%	945.526	0.12050	1.1
27.2779	0.00256	0.01%	361.01	0.026	0.1138	0.00021	0.19%	921.712	0.11190	1.7
23.4458	0.00098	0.00%	361.03	0.008	0.1057	0.00020	0.19%	898.428	0.10432	1.3
19.9279	0.00143	0.01%	361.03	0.003	0.09835	0.00021	0.21%	873.093	0.09686	1.5
16.9960	0.00150	0.01%	361.02	0.002	0.09133	0.00023	0.25%	847.750	0.09010	1.4
14.4946	0.00165	0.01%	361.03	0.001	0.08490	0.00013	0.15%	821.445	0.08372	1.4
12.5308	0.00110	0.01%	361.02	0.003	0.07910	0.00025	0.32%	796.260	0.07814	1.2
11.0672	0.00180	0.02%	361.03	0.004	0.07430	0.00010	0.13%	773.425	0.07347	1.1
9.5730	0.00095	0.01%	361.02	0.020	0.06862	0.00018	0.26%	744.654	0.06807	0.8
8.2745	0.00110	0.01%	361.04	0.002	0.06274	0.00004	0.07%	711.708	0.06245	0.5
7.5408	0.00097	0.01%	360.86	0.002	0.05911	0.00019	0.32%	688.828	0.05887	0.4
6.9291	0.00066	0.01%	360.86	0.003	0.05534	0.00010	0.18%	663.518	0.05517	0.3
6.5133	0.00101	0.02%	360.87	0.005	0.05244	0.00011	0.22%	641.726	0.05220	0.5
6.0259	0.00028	0.00%	360.87	0.011	0.04750	0.00005	0.11%	607.842	0.04792	-0.9
5.8026	0.00018	0.00%	360.89	0.003	0.04544	0.00002	0.05%	587.002	0.04548	-0.1
5.6195	0.00037	0.01%	360.87	0.007	0.04250	0.00006	0.15%	566.196	0.04317	-1.5
5.4177	0.00041	0.01%	360.87	0.001	0.03946	0.00009	0.24%	536.449	0.04007	-1.5
5.2923	0.00020	0.00%	360.87	0.002	0.03739	0.00008	0.22%	512.684	0.03776	-1.0
5.1362	0.00024	0.00%	360.87	0.002	0.03397	0.00007	0.22%	475.125	0.03438	-1.2
5.0380	0.00012	0.00%	360.86	0.004	0.03158	0.00007	0.22%	446.754	0.03203	-1.4
4.9379	0.00052	0.01%	360.87	0.003	0.02929	0.00006	0.19%	414.111	0.02953	-0.8
4.8875	0.00032	0.01%	360.86	0.004	0.02795	0.00010	0.37%	397.191	0.02831	-1.3
4.8051	0.00048	0.01%	360.87	0.002	0.02616	0.00013	0.48%	369.540	0.02644	-1.1
4.7545	0.00018	0.00%	360.88	0.003	0.02513	0.00012	0.48%	353.326	0.02541	-1.1
4.6503	0.00046	0.01%	360.86	0.002	0.02337	0.00011	0.47%	323.180	0.02361	-1.0
4.6197	0.00036	0.01%	360.88	0.002	0.02293	0.00005	0.20%	314.593	0.02312	-0.8
4.4840	0.00034	0.01%	360.87	0.006	0.02139	0.00007	0.33%	282.604	0.02143	-0.2
4.4083	0.00058	0.01%	360.87	0.003	0.02076	0.00012	0.56%	267.244	0.02068	0.4
4.2973	0.00080	0.02%	360.88	0.001	0.01979	0.00016	0.81%	247.407	0.01977	0.1

Pressure		s_p	s_p/p	T_{90}	s_T	η	s_η	s_η/η	ρ	η	$100(\eta_{\text{exp}}/\eta_{\text{calc}}-1)$
MPa	exp	MPa	%	K	K	mPa·s	mPa·s	%	kg·m ⁻³	mPa·s	%
	exp	exp	exp	exp	exp	exp	exp	exp	calc	calc	
3.0218	0.00078	0.00078	0.03%	360.84	0.064	0.01539	0.00002	0.12%	122.366	0.01502	2.4
2.0890	0.00202	0.00202	0.10%	360.89	0.014	0.01424	0.00009	0.66%	72.9842	0.01409	1.1
1.5169	0.00022	0.00022	0.01%	360.84	0.004	0.01389	0.00002	0.13%	49.3568	0.01376	0.9
1.1925	0.00009	0.00009	0.01%	360.85	0.009	0.01364	0.00001	0.08%	37.4214	0.01364	0.0
0.6503	0.00002	0.00002	0.00%	360.84	0.006	0.01367	0.00001	0.05%	19.3165	0.01348	1.4
0.5003	0.00001	0.00001	0.00%	360.84	0.011	0.01353	0.00001	0.06%	14.6517	0.01345	0.6
66.9514	0.01347	0.01347	0.02%	380.63	0.020	0.1604	0.00048	0.30%	1029.15	0.16177	-0.8
62.9384	0.00235	0.00235	0.00%	380.61	0.003	0.1548	0.00053	0.34%	1018.77	0.15559	-0.5
55.0768	0.00209	0.00209	0.00%	380.61	0.008	0.1439	0.00000	0.00%	996.279	0.14344	0.3
48.4214	0.00282	0.00282	0.01%	380.61	0.005	0.1341	0.00054	0.41%	974.509	0.13307	0.8
41.8511	0.00331	0.00331	0.01%	380.61	0.003	0.1242	0.00025	0.20%	949.687	0.12260	1.3
35.9052	0.00246	0.00246	0.01%	380.62	0.003	0.1143	0.00020	0.17%	923.296	0.11280	1.4
31.0439	0.00794	0.00794	0.03%	380.62	0.001	0.1059	0.00026	0.25%	897.836	0.10440	1.4
27.0333	0.00443	0.00443	0.02%	380.62	0.017	0.09850	0.00028	0.28%	873.097	0.09708	1.5
23.9710	0.00415	0.00415	0.02%	380.62	0.005	0.09284	0.00028	0.30%	851.049	0.09115	1.9
21.0921	0.00345	0.00345	0.02%	380.62	0.103	0.08694	0.00033	0.39%	826.862	0.08520	2.0
18.0965	0.00246	0.00246	0.01%	380.67	0.015	0.07971	0.00037	0.47%	796.346	0.07840	1.7
16.1222	0.00094	0.00094	0.01%	380.64	0.010	0.07458	0.00017	0.22%	772.230	0.07351	1.5
14.5487	0.00062	0.00062	0.00%	380.62	0.010	0.07006	0.00014	0.20%	749.517	0.06924	1.2
13.0609	0.00122	0.00122	0.01%	380.64	0.006	0.06579	0.00000	0.00%	723.815	0.06478	1.6
11.4234	0.00254	0.00254	0.02%	380.62	0.008	0.05996	0.00009	0.14%	688.635	0.05921	1.3
10.4004	0.00051	0.00051	0.00%	380.61	0.001	0.05572	0.00008	0.14%	660.764	0.05519	0.9
9.7883	0.00140	0.00140	0.01%	380.61	0.002	0.05305	0.00010	0.18%	640.801	0.05251	1.0
9.1990	0.00160	0.00160	0.02%	380.64	0.003	0.04993	0.00007	0.14%	618.035	0.04962	0.6
8.7395	0.00039	0.00039	0.00%	380.61	0.004	0.04732	0.00009	0.20%	597.515	0.04717	0.3
8.2071	0.00120	0.00120	0.01%	380.39	0.016	0.04465	0.00007	0.15%	570.645	0.04415	1.1
7.7120	0.00079	0.00079	0.01%	380.57	0.007	0.04060	0.00006	0.14%	536.172	0.04060	0.0
7.4310	0.00084	0.00084	0.01%	380.60	0.004	0.03865	0.00008	0.20%	513.451	0.03843	0.6
7.2041	0.00121	0.00121	0.02%	380.63	0.006	0.03677	0.00007	0.18%	492.664	0.03655	0.6

Pressure MPa	s_p MPa	s_p/p %	T_{90} K	s_T K	η mPa·s	s_η exp	s_η exp	s_η exp	s_η exp	ρ kg·m ⁻³	η calc	$100(\eta_{\text{exp}}/\eta_{\text{calc}} - 1)$ %
7.0002	0.00042	0.01%	380.60	0.004	0.03467	0.00005	0.00005	0.14%	0.14%	472.427	0.03481	-0.4
6.7565	0.00070	0.01%	380.62	0.002	0.03256	0.00003	0.00003	0.10%	0.10%	445.091	0.03261	-0.1
6.5512	0.00064	0.01%	380.63	0.003	0.03073	0.00003	0.00003	0.10%	0.10%	420.167	0.03072	0.0
6.3503	0.00017	0.00%	380.64	0.007	0.02897	0.00004	0.00004	0.13%	0.13%	394.349	0.02890	0.2
6.0979	0.00040	0.01%	380.62	0.035	0.02695	0.00002	0.00002	0.08%	0.08%	361.550	0.02675	0.8
6.0082	0.00047	0.01%	380.64	0.002	0.02629	0.00003	0.00003	0.10%	0.10%	349.617	0.02601	1.0
5.7473	0.00022	0.00%	380.62	0.015	0.02436	0.00008	0.00008	0.32%	0.32%	316.703	0.02411	1.0
5.5377	0.00034	0.01%	380.65	0.021	0.02307	0.00004	0.00004	0.16%	0.16%	291.542	0.02277	1.3
5.3272	0.00038	0.01%	380.62	0.001	0.02202	0.00002	0.00002	0.09%	0.09%	268.375	0.02162	1.8
5.0149	0.00056	0.01%	380.61	0.027	0.02038	0.00003	0.00003	0.13%	0.13%	237.161	0.02021	0.9
5.0128	0.00030	0.01%	380.58	0.016	0.02036	0.00006	0.00006	0.31%	0.31%	237.092	0.02021	0.8
4.8477	0.00076	0.02%	380.61	0.022	0.01969	0.00008	0.00008	0.42%	0.42%	222.039	0.01958	0.6
4.5192	0.00078	0.02%	380.63	0.003	0.01869	0.00004	0.00004	0.21%	0.21%	195.069	0.01854	0.8
2.7249	0.00136	0.05%	380.61	0.004	0.01562	0.00009	0.00009	0.57%	0.57%	91.9007	0.01525	2.4
2.1432	0.00106	0.05%	380.60	0.003	0.01499	0.00013	0.00013	0.88%	0.88%	68.0160	0.01482	1.2
1.6815	0.00212	0.13%	380.62	0.001	0.01482	0.00016	0.00016	1.08%	1.08%	51.0738	0.01457	1.7
0.9013	0.00003	0.00%	380.60	0.003	0.01434	0.00001	0.00001	0.06%	0.06%	25.6128	0.01427	0.5
0.6029	0.00005	0.01%	380.61	0.013	0.01420	0.00001	0.00001	0.06%	0.06%	16.7363	0.01419	0.1
17.4453	0.00057	0.00%	400.80	0.023	0.06571	0.00013	0.00013	0.19%	0.19%	721.832	0.064843	1.3
15.6338	0.00104	0.01%	400.82	0.002	0.06098	0.00009	0.00009	0.15%	0.15%	691.887	0.060132	1.4
14.3057	0.00124	0.01%	400.81	0.003	0.05747	0.00011	0.00011	0.19%	0.19%	665.685	0.056343	2.0
12.3619	0.00056	0.00%	400.74	0.057	0.05046	0.00003	0.00003	0.05%	0.05%	617.599	0.050091	0.7
11.6071	0.00052	0.00%	400.78	0.010	0.04765	0.00004	0.00004	0.09%	0.09%	593.885	0.047306	0.7
10.9246	0.00075	0.01%	400.76	0.007	0.04493	0.00005	0.00005	0.12%	0.12%	569.430	0.044614	0.7
10.3353	0.00062	0.01%	400.77	0.012	0.04253	0.00003	0.00003	0.07%	0.07%	544.974	0.042094	1.0
9.8402	0.00045	0.00%	400.73	0.118	0.04011	0.00001	0.00001	0.03%	0.03%	521.910	0.039861	0.6
9.3162	0.00031	0.00%	400.76	0.007	0.03753	0.00002	0.00002	0.06%	0.06%	493.693	0.037308	0.6
8.9189	0.00038	0.00%	400.77	0.012	0.03519	0.00007	0.00007	0.20%	0.20%	469.839	0.03529	-0.3
8.5269	0.00009	0.00%	400.76	0.001	0.03319	0.00002	0.00002	0.06%	0.06%	444.088	0.033245	-0.2

Pressure MPa	s_p MPa	s_p/p %	T_{90} K	s_T K	η mPa·s	s_η mPa·s	s/η %	ρ kg·m ⁻³	η calc	$100(\eta_{\text{exp}}/\eta_{\text{calc}} - 1)$ %
exp	exp	exp	exp	exp	exp	exp	exp	calc	calc	
8.1074	0.00044	0.01%	400.77	0.006	0.03128	0.00008	0.26%	413.952	0.03102	0.8
7.7714	0.00069	0.01%	400.67	0.015	0.02928	0.00003	0.11%	388.904	0.029294	0.0
7.6352	0.00053	0.01%	400.77	0.005	0.02836	0.00006	0.23%	377.709	0.028563	-0.7
7.2407	0.00018	0.00%	400.75	0.003	0.02626	0.00007	0.27%	346.429	0.026624	-1.4
6.9366	0.00018	0.00%	400.77	0.001	0.02507	0.00007	0.28%	322.159	0.025231	-0.7
6.6175	0.00057	0.01%	400.74	0.003	0.02383	0.00002	0.10%	297.335	0.023899	-0.3
6.2883	0.00072	0.01%	400.77	0.001	0.02249	0.00002	0.11%	272.421	0.02266	-0.8
5.9058	0.00042	0.01%	400.76	0.003	0.02140	0.00003	0.15%	245.131	0.021406	0.0
5.6187	0.00030	0.01%	400.77	0.006	0.02058	0.00001	0.06%	225.832	0.020585	0.0
5.0568	0.00043	0.01%	400.74	0.006	0.01953	0.00001	0.03%	191.191	0.01924	1.5
4.6387	0.00050	0.01%	400.74	0.009	0.01871	0.00002	0.13%	167.892	0.018427	1.5
4.3024	0.00100	0.02%	400.76	0.029	0.01811	0.00005	0.25%	150.533	0.01787	1.3
3.7472	0.00025	0.01%	400.79	0.004	0.01724	0.00002	0.11%	124.356	0.016829	2.5
3.1226	0.00094	0.03%	400.80	0.023	0.01652	0.00009	0.55%	98.0847	0.016217	1.9
2.3031	0.00095	0.04%	400.77	0.011	0.01596	0.00008	0.48%	67.7448	0.015625	2.1
1.6807	0.00311	0.19%	400.75	0.035	0.01562	0.00012	0.75%	47.2314	0.015295	2.1
0.8915	0.00006	0.01%	400.77	0.004	0.01503	0.00001	0.07%	23.7507	0.014989	0.3
0.6049	0.00002	0.00%	400.77	0.023	0.01513	0.00002	0.11%	15.8246	0.014902	1.6
0.3993	0.00001	0.00%	400.76	0.042	0.01499	0.00001	0.09%	10.3145	0.014846	1.0
0.2007	0.00000	0.00%	400.78	0.008	0.01477	0.00002	0.10%	5.12220	0.014798	-0.2
0.0977	0.00000	0.00%	400.75	0.016	0.01458	0.00005	0.32%	2.47845	0.014774	-1.3
69.4130	0.00349	0.01%	401.17	0.007	0.1487	0.00029	0.19%	1005.49	0.15001	-0.8
58.5830	0.00302	0.01%	401.18	0.021	0.1340	0.00044	0.33%	974.412	0.13425	-0.2
50.3261	0.00181	0.00%	401.13	0.019	0.1223	0.00011	0.09%	946.282	0.12214	0.1
44.7440	0.01101	0.02%	401.14	0.007	0.1151	0.00021	0.18%	924.096	0.11376	1.2
39.4312	0.00296	0.01%	401.18	0.005	0.1065	0.00018	0.17%	899.768	0.10554	0.9
35.0732	0.00291	0.01%	401.13	0.002	0.09949	0.00034	0.34%	876.865	0.098592	0.9
31.1521	0.00241	0.01%	401.15	0.019	0.09334	0.00013	0.14%	852.942	0.092022	1.4
25.9668	0.00284	0.01%	401.17	0.002	0.08429	0.00014	0.17%	814.669	0.082733	1.9

Pressure MPa	s_p MPa	s_p/p %	T_{90} K	s_T K	η mPa·s	s_η mPa·s	s_η/η %	ρ kg·m ⁻³	η calc	$100(\eta_{\text{exp}}/\eta_{\text{calc}} - 1)$ %
exp	exp	exp	exp	exp	exp	exp	exp	calc	calc	
24.0301	0.00114	0.00%	401.13	0.001	0.08019	0.00022	0.27%	797.761	0.079035	1.5
22.0707	0.00257	0.01%	401.15	0.005	0.07618	0.00020	0.26%	778.429	0.075073	1.5
18.9123	0.00394	0.02%	401.16	0.004	0.06917	0.00009	0.13%	741.342	0.068164	1.5
17.5253	0.00043	0.00%	401.16	0.003	0.06585	0.00006	0.09%	721.850	0.064853	1.5
13.2314	0.00107	0.01%	400.82	0.003	0.05350	0.00006	0.11%	640.719	0.052992	1.0
65.9479	0.00680	0.01%	421.19	0.005	0.13014	0.00059	0.45%	967.264	0.13253	-1.8
59.5091	0.00448	0.01%	421.15	0.012	0.12219	0.00014	0.12%	946.976	0.12366	-1.2
53.3955	0.00220	0.00%	421.15	0.002	0.11469	0.00035	0.30%	925.180	0.11514	-0.4
45.8819	0.00279	0.01%	421.15	0.003	0.10461	0.00018	0.17%	893.994	0.10446	0.1
42.1259	0.00366	0.01%	421.13	0.003	0.09904	0.00029	0.30%	876.041	0.09898	0.1
37.1835	0.00278	0.01%	421.15	0.003	0.09176	0.00039	0.42%	849.056	0.09154	0.2
33.1701	0.00246	0.01%	421.20	0.003	0.08581	0.00036	0.42%	823.439	0.08520	0.7
30.1923	0.00119	0.00%	421.13	0.008	0.08117	0.00046	0.57%	801.843	0.08033	1.0
27.1034	0.00330	0.01%	421.14	0.003	0.07554	0.00053	0.70%	775.952	0.07499	0.7
24.0215	0.00070	0.00%	421.15	0.017	0.06976	0.00005	0.07%	745.523	0.06931	0.7
22.1229	0.00075	0.00%	421.12	0.014	0.06617	0.00019	0.28%	723.777	0.06559	0.9
19.5737	0.00271	0.01%	421.15	0.003	0.06072	0.00008	0.13%	689.315	0.06020	0.9
18.2442	0.00138	0.01%	421.14	0.004	0.05760	0.00018	0.32%	668.355	0.05719	0.7
16.7863	0.00044	0.00%	421.14	0.002	0.05412	0.00014	0.27%	642.041	0.05367	0.8
15.5266	0.00033	0.00%	421.14	0.002	0.05077	0.00018	0.35%	615.744	0.05040	0.7
14.6022	0.00076	0.01%	421.14	0.003	0.04824	0.00016	0.32%	593.788	0.04786	0.8
13.5912	0.00133	0.01%	421.16	0.003	0.04486	0.00006	0.13%	566.380	0.04488	-0.1
12.9239	0.00029	0.00%	421.14	0.018	0.04301	0.00008	0.20%	546.115	0.04282	0.4
12.9194	0.00047	0.00%	421.20	0.110	0.04302	0.00009	0.20%	545.753	0.04279	0.5
12.0189	0.00050	0.00%	421.14	0.004	0.03969	0.00009	0.23%	515.039	0.03987	-0.4
11.3411	0.00126	0.01%	421.14	0.008	0.03746	0.00007	0.18%	488.646	0.03754	-0.2
10.8415	0.00184	0.02%	421.15	0.004	0.03615	0.00001	0.02%	467.211	0.03577	1.1
10.2561	0.00099	0.01%	421.14	0.002	0.03377	0.00008	0.25%	440.045	0.03365	0.3
9.8079	0.00157	0.02%	421.14	0.006	0.03202	0.00009	0.28%	417.678	0.03202	0.0

Pressure MPa	s_p MPa	s_p/p %	T_{90} K	s_T K	η mPa·s	s_η mPa·s	s/η %	ρ kg·m ⁻³	η calc	$100(\eta_{\text{exp}}/\eta_{\text{calc}} - 1)$ %
exp	exp	exp	exp	exp	exp	exp	exp	calc	calc	
9.3565	0.00136	0.01%	421.17	0.002	0.03009	0.00008	0.27%	393.742	0.03037	-1.0
8.8607	0.00050	0.01%	421.15	0.003	0.02825	0.00008	0.27%	366.496	0.02862	-1.3
8.4563	0.00206	0.02%	421.13	0.006	0.02716	0.00006	0.23%	343.642	0.02725	-0.3
8.0534	0.00038	0.00%	421.18	0.032	0.02563	0.00003	0.11%	320.384	0.02593	-1.2
7.6449	0.00129	0.02%	421.17	0.001	0.02439	0.00002	0.10%	297.069	0.02470	-1.3
7.2409	0.00091	0.01%	421.15	0.003	0.02331	0.00005	0.23%	274.337	0.02357	-1.1
6.7972	0.00142	0.02%	421.15	0.002	0.02216	0.00004	0.20%	249.986	0.02244	-1.3
6.1984	0.00165	0.03%	421.15	0.006	0.02081	0.00004	0.17%	218.595	0.02111	-1.5
5.6805	0.00062	0.01%	421.15	0.003	0.01974	0.00002	0.11%	193.048	0.02013	-1.9
5.1142	0.00149	0.03%	421.13	0.006	0.01909	0.00005	0.25%	166.957	0.01921	-0.6
4.6639	0.00102	0.02%	421.16	0.002	0.01852	0.00003	0.16%	147.499	0.01858	-0.3
4.0092	0.00538	0.13%	421.15	0.002	0.01770	0.00007	0.40%	121.264	0.01761	0.5
3.2642	0.00113	0.03%	421.18	0.004	0.01721	0.00002	0.11%	94.0345	0.01696	1.5
2.5817	0.00270	0.10%	421.17	0.002	0.01658	0.00002	0.13%	71.2975	0.01649	0.6
1.8733	0.00063	0.03%	421.15	0.006	0.01623	0.00004	0.28%	49.6337	0.01610	0.8
1.2269	0.00006	0.00%	421.14	0.002	0.01599	0.00001	0.07%	31.3629	0.01582	1.1
0.6732	0.00007	0.01%	421.15	0.008	0.01573	0.00001	0.08%	16.7126	0.01563	0.7
0.5976	0.00004	0.01%	421.17	0.049	0.01575	0.00002	0.15%	14.7772	0.01561	0.9
0.4030	0.00000	0.00%	421.10	0.007	0.01600	0.00002	0.12%	9.86883	0.01555	2.9
0.1977	0.00000	0.00%	421.15	0.003	0.01581	0.00004	0.25%	4.79132	0.01549	2.0
0.0998	0.00000	0.00%	421.16	0.007	0.01560	0.00003	0.18%	2.40693	0.01547	0.9
65.0376	0.00207	0.00%	299.47	0.010	0.2593	0.00125	0.48%	1153.08	0.26257	-1.3
49.9538	0.00042	0.00%	299.66	0.001	0.2294	0.00009	0.04%	1123.13	0.22945	0.0
39.3854	0.03559	0.09%	299.84	0.009	0.2085	0.00041	0.20%	1097.99	0.20668	0.9
30.5025	0.01006	0.03%	300.04	0.012	0.1888	0.00107	0.57%	1072.92	0.18741	0.7
22.6122	0.00287	0.01%	300.23	0.007	0.1715	0.00033	0.19%	1046.26	0.16984	1.0
16.5127	0.01779	0.11%	300.42	0.008	0.1576	0.00027	0.17%	1021.26	0.15553	1.3
11.6131	0.00378	0.03%	300.57	0.007	0.1438	0.00018	0.12%	996.949	0.14326	0.3
7.2275	0.00413	0.06%	300.71	0.004	0.1320	0.00020	0.15%	970.047	0.13122	0.6

Pressure MPa	s_p MPa	s_p/p %	T_{90} K	s_T K	η mPa·s	s_η mPa·s	s/η %	ρ kg·m ⁻³	η mPa·s	$100(\eta_{\text{exp}}/\eta_{\text{calc}} - 1)$ %
exp	exp	exp	exp	exp	exp	exp	exp	calc	calc	
3.7057	0.01471	0.40%	300.89	0.008	0.1205	0.00010	0.08%	942.131	0.12016	0.3
1.9517	0.00351	0.18%	301.02	0.006	0.1138	0.00016	0.14%	924.486	0.11381	0.0
66.9901	0.00355	0.01%	320.76	0.002	0.2262	0.00054	0.24%	1121.94	0.22927	-1.4
51.3388	0.00149	0.00%	320.72	0.005	0.2002	0.00054	0.27%	1088.41	0.19896	0.6
43.3629	0.01198	0.03%	320.72	0.008	0.1844	0.00021	0.11%	1068.05	0.18363	0.4
34.8497	0.00468	0.01%	320.75	0.001	0.1684	0.00027	0.16%	1042.71	0.16705	0.8
27.9154	0.00373	0.01%	320.73	0.004	0.1543	0.00039	0.25%	1018.35	0.15322	0.7
22.1610	0.00280	0.01%	320.68	0.004	0.1426	0.00057	0.40%	994.388	0.14123	1.0
17.8089	0.00181	0.01%	320.72	0.005	0.1329	0.00053	0.40%	972.706	0.13153	1.1
13.7702	0.00634	0.05%	320.73	0.007	0.1227	0.00024	0.19%	948.755	0.12188	0.7
9.9648	0.00311	0.03%	320.74	0.004	0.1125	0.00010	0.08%	920.829	0.11182	0.6
6.9686	0.00376	0.05%	320.75	0.009	0.1034	0.00014	0.14%	892.630	0.10277	0.6
4.8471	0.00247	0.05%	320.73	0.003	0.09551	0.00007	0.07%	866.859	0.09532	0.2
3.3787	0.00180	0.05%	320.75	0.013	0.08897	0.00013	0.14%	843.402	0.08914	-0.2
2.1970	0.00707	0.32%	320.72	0.016	0.08315	0.00017	0.20%	818.374	0.08312	0.0
65.9207	0.00486	0.01%	341.07	0.022	0.1966	0.00032	0.16%	1087.45	0.19951	-1.4
55.8547	0.00871	0.02%	341.05	0.009	0.1807	0.00053	0.29%	1064.23	0.18169	-0.5
47.3801	0.00681	0.01%	341.08	0.057	0.1661	0.00074	0.44%	1041.55	0.16667	-0.3
33.4931	0.00213	0.01%	341.03	0.009	0.1422	0.00026	0.18%	995.411	0.14158	0.5
27.5033	0.00598	0.02%	341.06	0.009	0.1311	0.00023	0.18%	969.872	0.13009	0.8
22.6338	0.00435	0.02%	341.04	0.020	0.1219	0.00019	0.15%	945.179	0.12024	1.4
18.8948	0.00319	0.02%	341.05	0.003	0.1127	0.00033	0.29%	922.580	0.11214	0.5
15.0210	0.00081	0.01%	341.06	0.008	0.1035	0.00023	0.23%	894.167	0.10298	0.5
11.9852	0.00322	0.03%	341.06	0.022	0.09520	0.00023	0.25%	866.329	0.09495	0.3
10.0071	0.00193	0.02%	341.03	0.018	0.08917	0.00016	0.17%	843.981	0.08908	0.1
8.0548	0.00215	0.03%	341.04	0.024	0.08248	0.00017	0.20%	816.246	0.08243	0.1
7.0086	0.00113	0.02%	341.07	0.014	0.07836	0.00022	0.29%	797.612	0.07831	0.1
6.0735	0.00215	0.04%	341.06	0.012	0.07408	0.00017	0.23%	777.502	0.07415	-0.1

NIST Author Manuscript

NIST Author Manuscript

NIST Author Manuscript

Pressure	s_p	s_p/p	T_{90}	s_T	η	s_η	s_η/η	ρ	η	$100(\eta_{\text{exp}}/\eta_{\text{calc}} - 1)$
MPa	MPa	%	K	K	mPa·s	mPa·s	%	kg·m ⁻³	mPa·s	%
exp	exp	exp	exp	exp	exp	exp	exp	calc	calc	
5.0085	0.00147	0.03%	340.92	0.023	0.06770	0.00006	0.09%	748.407	0.06859	-1.3