

Viscosity Measurements and Model Comparisons for the Refrigerant Blends R-410A and R-507A

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ABSTRACT

Wide-ranging viscosity measurements of the blends R-410A (0.5 R-32 + 0.5 R-125 by mass) and R-507A (0.5 R-143a + 0.5 R-125 by mass) were carried out in a torsional crystal viscometer at two subcritical and three supercritical isotherms between 300 and 420 K with pressures up to 82 MPa. Considerable conductances were observed in the blend containing difluoromethane (R-32). Therefore, reference viscosity measurements of the blend R-410A were carried out at saturated-liquid conditions between 240 K and 310 K with a sealed gravitational capillary viscometer, because in that instrument the sample is not exposed to an electric field. The measurement results are compared with values estimated via the extended-corresponding-states model in NIST Standard Reference Database 23 (REFPROP, version 7.0) and with literature data. For both blends, the results obtained with the torsional crystal viscometer agree with the predicted viscosities within the estimated experimental uncertainty of the instrument at low sample conductances. The deviations increase systematically with the sample conductance. The data for R-410A obtained with the capillary viscometer agree with the estimated viscosities within their experimental uncertainty. Literature data deviations range from -18% to 5% for this blend and from -9% to 14% for R-507A, while the R-507A-measurements of this work agree with the model viscosities within $\pm 4\%$.

INTRODUCTION

Significant energy penalties have been measured in HVAC systems with next-generation alternative refrigerant blends operating at condenser temperatures that are closer to the critical temperatures of the blends. To understand these energy penalties, working fluids have to be characterized not

only at subcritical saturated-vapor and liquid states but also at supercritical conditions. Literature viscosity data for such blends and working conditions are very sparse. Accordingly narrow is the basis on which predictive viscosity models for such mixtures have been developed. Besides, substantial errors have been identified frequently in literature viscosity data for hydrofluorocarbon systems. Therefore, additional viscosity measurements are needed to broaden the base of validated and reliable data for these important fluids. Measuring the blend R-410A in two different viscometers presented an opportunity to discern the susceptibility of this fluid to an applied electric field and to quantify electroviscous effects in the results of the torsional crystal viscometer.

The report is organized as follows. In an experimental section, the preparation of the mixture samples is described, and the torsional crystal viscometer and data analysis are explained. Results and comparisons with the extended-corresponding-states viscosity model and literature data are presented first for the blend R-507A, then for R-410A, because the measurements of the latter were more complex.

EXPERIMENTAL SECTION

Mixture Preparation

The test mixtures R-410A (R-32/125) and R-507A (R-125/143a) were prepared gravimetrically in aluminum cylinders with a volume of 15.8 dm^3 from high-purity components. R-32 (difluoromethane, CH_2F_2) and R-125 (pentafluoroethane, C_2HF_5) were "electronic grade" materials. The manufacturer's specification stated a minimum purity of 99.99% with a water content less than 5 ppm. In-house gas chromatographic analysis confirmed the high purity apart from a small

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Table 1. Constituents of the Test Mixtures and Their Compositions in Mole Fractions x and Mass Fractions w . The Uncertainty of the Mass Fractions is ± 0.00002

| | Component 1 | Component 2 | x_1 | x_2 | w_1 | w_2 |
|--------|-------------|-------------|---------|---------|---------|---------|
| R-410A | R-32 | R-125 | 0.69767 | 0.30233 | 0.50007 | 0.49993 |
| R-507A | R-143a | R-125 | 0.58832 | 0.41168 | 0.50016 | 0.49984 |

amount of air in the vapor phase. R-143a (1,1,1-trifluoroethane, $\text{CH}_3\text{-CF}_3$) was refrigerant-grade material. Our analysis indicated a purity of 99.93%. Air and any other light inorganics, which may have been present in the components, were removed by repeatedly freezing the sample in liquid nitrogen, evacuating the vapor space, and thawing. The target compositions for both blends were 0.50 by mass fraction. The actual compositions of the test samples are given in Table 1.

Torsional Crystal Viscometer

The measuring element in the torsional crystal viscometer is a piezoelectric quartz crystal of cylindrical shape. The crystal is mounted in a transducer and driven into a torsional oscillation by an ac voltage applied to two of four surrounding brass electrodes. The frequency of the voltage is varied through the mechanical resonance of the crystal. The resonant frequency and the bandwidth of the resonance depend on the damping by the fluid surrounding the crystal. Absolute measurements of fluids can be performed by comparing the damping to that *in vacuo*. The technique and details of the instrument were described by Diller and Frederick (1989) and by Hafer and Laesecke (2003).

The working equation for absolute viscosity measurements with the torsional crystal viscometer in the frequency domain is

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

where η denotes the viscosity of the fluid, ρ its density, m the mass and S the surface area of the crystal, f^* the resonant frequency, and Δf the bandwidth of the resonance. Subscript 0 indicates vacuum conditions. Since the technique measures the product $(\eta \times \rho)$, the density of the fluid must be obtained separately in order to determine its viscosity and the uncertainty of the density propagates into the uncertainty of the viscosity measurement. In this work, densities of the refrigerant blends were calculated for the measured compositions, pressures, and temperatures with the mixture models in NIST Standard Reference Database 23, REFPROP (Lemmon et al. 2002). Their estimated uncertainty is $\pm 0.1\%$.

The viscosity measurements were carried out with the cylindrical quartz crystal "D" (diameter $d = 3.046$ mm, length $L = 50.076$ mm, mass $m = 0.9662$ g) in the transducer of the viscometer. The resonance of the crystal *in vacuo* depends on the applied voltage to drive the torsional crystal vibration and on temperature. The change of the resonant frequency f_0^* and

of the resonance bandwidth f_0 with these variables was measured after the measurements of the refrigerant blends with drive voltages from 5 mV to 1.1 V in the temperature range from 300 K to 460 K. The results confirmed previous measurements in 1996 and in 1998, which indicates a remarkable long-term stability of the transducer. The data from the vacuum measurements of the transducer were correlated for each drive voltage by a polynomial in temperature. The resonant frequency f_0^* follows closely a quadratic polynomial with a maximum of 39.546 kHz at 369 K. The bandwidth f_0 varies in this temperature range from 0.07 Hz to 2 Hz. Its logarithm can be regressed in terms of a cubic polynomial in temperature. These correlations were used in the analysis of the measurements of the refrigerant blends. The accurate determination of the voltage and temperature dependence of the crystal vibration *in vacuo* made it possible to expand the range of operation of the viscometer from saturated or compressed liquids to dilute gases, thus covering a wide range of fluid states with one transducer.

The measurement strategy in the torsional crystal viscometer aimed to use the limited sample amount most economically. First, vapor from a heated sample cylinder was condensed through the heated filling system of the viscometer into the stainless-steel high-pressure cell while that was cooled with liquid nitrogen below 200 K. The filling of the cell could be monitored by setting the impedance analyzer to 39 kHz and reading the complex admittance $Y = G + jB$ of the torsional crystal transducer in the cell. The susceptance B indicates the susceptance of the dielectric between the electrodes of the transducer. The reference is the permittivity $B_0 = 34.17 \mu\text{S}$ *in vacuo*. When the transducer was fully immersed in liquid sample, the cell was returned to 300 K and the maximum pressure by isochoric heating. The semi-automated viscometer was programmed with the desired target pressures, and the measurements were carried out at constant temperature under computer control to a pressure near saturation. The cell was then heated to 420 K to raise the pressure to the starting pressure for that isotherm. When the isotherm was completed, the viscometer was evacuated and then refilled for each of the remaining isotherms at 340 K, 360 K, and 390 K; R-507A was measured first and R-410A second.

The measurements consist of frequency scans of the transducer resonance in the sample fluid at every pressure of each isotherm and at several drive voltages. Resolving the dependence of the resonance on the drive voltage allows extrapolation to the resonance at zero drive voltage, which is consistent with the definition of Newtonian viscosity as a property characterizing momentum transport in the limit of

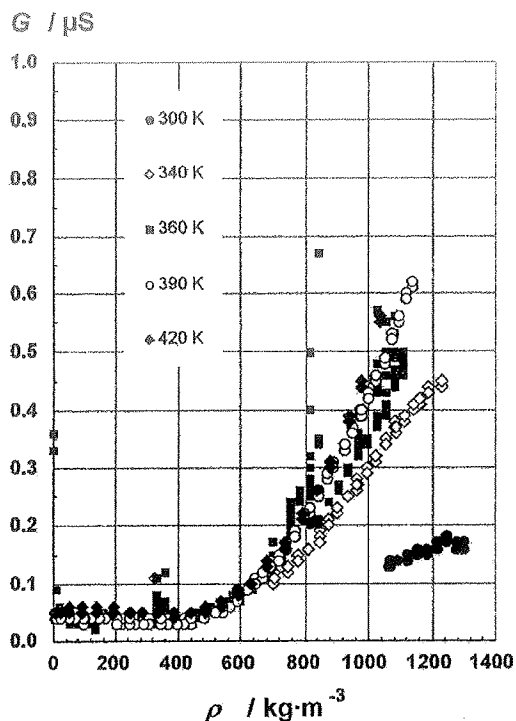


Figure 1 Conductances G at 39 kHz of the mixture R-507A (0.5 R-143a + 0.5 R-125 by mass) as measured in the torsional crystal viscometer.

zero shear. Due to the resolution limits of the impedance analyzer, the majority of the measurements were limited to drive voltages from 0.1 V to 1.1 V. Lower voltages, down to 10 mV, could be applied only in a few cases of dilute gases. For reasons of consistency, all the results reported in this work were derived from resonance scans with drive voltages of 0.1 V. The uncertainty of measurements with the torsional crystal viscometer typically does not exceed $\pm 2\%$. Measurements of fluids with a background conductance G at 39 kHz of more than $1 \mu\text{S}$ may be influenced by electroviscous effects because the sample fluid is affected by the applied drive voltage.

The experimental viscosities measured with the torsional crystal viscometer were compared with viscosities calculated with the extended corresponding states model in REFPROP (Klein et al. 1997; Lemmon et al. 2002) using the recently developed correlation for the viscosity of R-134a as the reference fluid (Huber et al. 2003). They were also compared with literature data. In the following, the results will be presented for each blend, and their reliability will be discussed.

RESULTS AND DISCUSSION

Results for R-507A

The impedance analyzer in the viscometer measures the conductance G (in units of siemens or reciprocal ohm) of an

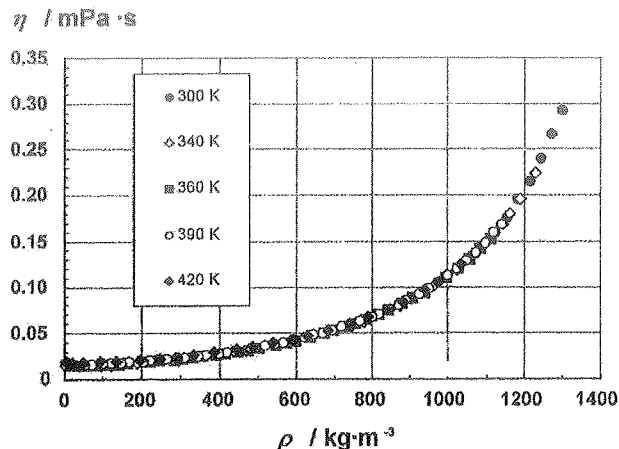


Figure 2 Density dependence of experimental viscosities of the mixture of R-507A (0.5 R-143a + 0.5 R-125 by mass) as measured in the torsional crystal viscometer.

electrical circuit that includes the transducer with the crystal and the surrounding fluid in the cell. The conductance values far away from the mechanical resonant frequency of the vibrating crystal provide valuable information about the sample fluid and its polarity because measurements of fluids with elevated background conductance ($G > 1 \mu\text{S}$) may be influenced by electroviscous effects when the sample fluid becomes susceptible to the applied drive voltage. HFC refrigerants are rather polar compounds.

Figure 1 shows the measured conductances G at 39 kHz of the blend R-507A as a function of density. Any increase of the conductance beyond that of the instrument circuitry when the cell is evacuated indicates the presence of charge carriers in the sample. No increase of the conductances of R-507A occurs up to a density of about $500 \text{ kg}\cdot\text{m}^{-3}$. At higher densities, the conductances increase with both density and temperature. While the increase is monotonic at 360 K and above, a flattening is observed on the isotherms at 300 K and 340 K beginning at about $1100 \text{ kg}\cdot\text{m}^{-3}$. The highest conductance of $G = 0.62 \mu\text{S}$ was measured at the highest pressure of the 390 K-isotherm. The scatter of the conductances at 360 K was caused by intermittent problems with an electrical connection in the instrument circuitry.

The viscosities for the blend R-507A measured in the torsional crystal viscometer are tabulated in Table 2. Their density dependence is displayed in Figure 2. Due to the measurements at supercritical temperatures, the entire density range from $0.09 \text{ kg}\cdot\text{m}^{-3}$ to $1300 \text{ kg}\cdot\text{m}^{-3}$ is covered and a large data gap existing in the literature has been filled. Figure 2 shows that the viscosity data aggregate along a single line with a barely discernible temperature dependence. This depen-

Table 2 . Experimental Viscosities of the Mixture R-507A (0.5 R-143a + 0.5 R-125 by mass) as Measured in the Torsional Crystal Viscometer

The contents of each line represents the average of four measurements. The precision of the measurements is indicated by the relative standard deviation of the viscosity averaging, s_{η}/η . Calculated density values were obtained from REFPROP version 7.0.

| P | T | ρ | η | s_{η}/η |
|----------|----------|--------------------|----------|-----------------|
| MPa | K | kg·m ⁻³ | mPa·s | % |
| measured | measured | calculated | measured | measured |
| 66.852 | 301.29 | 1299.9 | 0.2924 | 0.73 |
| 54.147 | 300.79 | 1273.7 | 0.2661 | 0.82 |
| 41.734 | 300.52 | 1243.1 | 0.2395 | 0.32 |
| 31.904 | 300.33 | 1213.8 | 0.2156 | 0.29 |
| 23.731 | 300.15 | 1184.7 | 0.1968 | 0.63 |
| 16.841 | 299.99 | 1154.7 | 0.1763 | 0.30 |
| 11.202 | 299.85 | 1124.4 | 0.1599 | 0.32 |
| 6.595 | 299.74 | 1092.9 | 0.1457 | 0.26 |
| 3.575 | 299.66 | 1066.6 | 0.1344 | 0.56 |
| 67.754 | 340.65 | 1229.9 | 0.2239 | 0.34 |
| 52.722 | 340.65 | 1190.4 | 0.1960 | 0.24 |
| 44.042 | 340.66 | 1162.8 | 0.1804 | 0.42 |
| 38.680 | 340.65 | 1143.3 | 0.1688 | 0.48 |
| 31.652 | 340.64 | 1113.8 | 0.1537 | 0.16 |
| 25.845 | 340.66 | 1084.5 | 0.1414 | 0.83 |
| 20.764 | 340.65 | 1053.5 | 0.1297 | 0.10 |
| 16.782 | 340.65 | 1023.7 | 0.1187 | 0.39 |
| 13.648 | 340.66 | 994.87 | 0.1097 | 0.13 |
| 11.013 | 340.66 | 964.72 | 0.1013 | 0.20 |
| 8.961 | 340.67 | 934.99 | 0.09395 | 0.10 |
| 7.292 | 340.66 | 903.87 | 0.08628 | 0.17 |
| 6.043 | 340.67 | 872.99 | 0.07944 | 0.16 |
| 5.204 | 340.65 | 845.52 | 0.07488 | 0.27 |
| 4.437 | 340.66 | 809.83 | 0.06844 | 0.14 |
| 3.986 | 340.66 | 778.36 | 0.06222 | 0.18 |
| 3.686 | 340.65 | 745.40 | 0.05733 | 0.19 |
| 3.485 | 340.66 | 702.86 | 0.05213 | 0.14 |
| 3.059 | 340.65 | 188.16 | 0.01693 | 0.14 |
| 2.767 | 340.66 | 152.43 | 0.01626 | 0.85 |
| 2.394 | 340.66 | 119.14 | 0.01526 | 1.75 |
| 2.053 | 340.68 | 94.811 | 0.01457 | 1.12 |
| 1.598 | 340.66 | 68.140 | 0.01462 | 0.57 |
| 1.002 | 340.67 | 39.186 | 0.01422 | 0.61 |
| 0.2657 | 340.66 | 9.5314 | 0.01401 | 0.27 |

Table 2 (continued). Experimental Viscosities of the Mixture R-507A (0.5 R-143a + 0.5 R-125 by mass) as Measured in the Torsional Crystal Viscometer

The contents of each line represents the average of four measurements. The precision of the measurements is indicated by the relative standard deviation of the viscosity averaging, s_η/η . Calculated density values were obtained from REFPROP version 7.0.

| p | T | ρ | η | s_η/η |
|----------|----------|--------------------|----------|---------------|
| MPa | K | kg·m ⁻³ | mPa·s | % |
| measured | measured | calculated | measured | measured |
| 0.1379 | 340.66 | 4.8807 | 0.01399 | 0.47 |
| 41.677 | 360.73 | 1110.7 | 0.1528 | 0.52 |
| 35.317 | 360.64 | 1082.6 | 0.1424 | 0.47 |
| 30.070 | 360.59 | 1055.4 | 0.1309 | 0.61 |
| 25.406 | 360.57 | 1026.5 | 0.1202 | 0.25 |
| 21.176 | 360.58 | 994.88 | 0.1100 | 0.26 |
| 15.366 | 360.58 | 936.84 | 0.09440 | 0.19 |
| 13.105 | 360.57 | 906.12 | 0.08756 | 0.03 |
| 11.389 | 360.58 | 877.17 | 0.08149 | 0.20 |
| 9.808 | 360.58 | 843.45 | 0.07465 | 0.00 |
| 8.833 | 360.59 | 817.14 | 0.06996 | 0.16 |
| 7.799 | 360.56 | 781.74 | 0.06453 | 0.34 |
| 7.240 | 360.59 | 756.74 | 0.06060 | 0.33 |
| 6.723 | 360.59 | 727.86 | 0.05657 | 0.23 |
| 6.306 | 360.59 | 697.76 | 0.05249 | 0.16 |
| 6.035 | 360.60 | 672.73 | 0.04976 | 0.14 |
| 5.722 | 360.57 | 635.44 | 0.04534 | 0.27 |
| 5.494 | 360.58 | 598.14 | 0.04161 | 0.34 |
| 5.379 | 360.57 | 574.98 | 0.03946 | 0.14 |
| 5.262 | 360.58 | 546.64 | 0.03690 | 0.17 |
| 5.121 | 360.60 | 506.00 | 0.03376 | 0.26 |
| 5.022 | 360.58 | 475.04 | 0.03149 | 0.10 |
| 4.938 | 360.59 | 446.97 | 0.02985 | 0.17 |
| 4.839 | 360.59 | 414.73 | 0.02766 | 0.05 |
| 4.766 | 360.59 | 391.82 | 0.02633 | 0.12 |
| 4.650 | 360.59 | 358.54 | 0.02459 | 0.31 |
| 4.547 | 360.57 | 332.91 | 0.02318 | 0.14 |
| 4.421 | 360.58 | 305.30 | 0.02203 | 0.07 |
| 4.306 | 360.60 | 283.26 | 0.02106 | 0.20 |
| 4.064 | 360.59 | 245.19 | 0.01980 | 0.08 |
| 3.885 | 360.59 | 222.05 | 0.01906 | 0.24 |
| 3.294 | 360.57 | 163.51 | 0.01737 | 0.48 |
| 2.901 | 360.58 | 133.80 | 0.01653 | 0.38 |
| 2.498 | 360.58 | 108.04 | 0.01586 | 0.23 |
| 1.980 | 360.59 | 79.759 | 0.01529 | 0.79 |

Table 2 (continued). Experimental Viscosities of the Mixture R-507A (0.5 R-143a + 0.5 R-125 by mass) as Measured in the Torsional Crystal Viscometer

The contents of each line represents the average of four measurements. The precision of the measurements is indicated by the relative standard deviation of the viscosity averaging, s_η/η . Calculated density values were obtained from REFPROP version 7.0.

| p | T | ρ | η | s_η/η |
|----------|----------|--------------------|----------|---------------|
| MPa | K | kg·m ⁻³ | mPa·s | % |
| measured | measured | calculated | measured | measured |
| 1.331 | 360.49 | 49.751 | 0.01486 | 0.09 |
| 0.5645 | 360.56 | 19.549 | 0.01442 | 0.04 |
| 0.2893 | 360.59 | 9.7744 | 0.01419 | 0.22 |
| 66.793 | 391.03 | 1139.6 | 0.1685 | 0.26 |
| 60.494 | 390.84 | 1120.4 | 0.1592 | 0.27 |
| 53.893 | 390.77 | 1097.6 | 0.1482 | 0.25 |
| 47.712 | 390.78 | 1073.2 | 0.1379 | 0.37 |
| 42.065 | 390.78 | 1047.8 | 0.1289 | 0.43 |
| 37.422 | 390.77 | 1023.9 | 0.1201 | 0.25 |
| 33.137 | 390.78 | 998.55 | 0.1125 | 0.61 |
| 29.530 | 390.77 | 974.01 | 0.1052 | 0.10 |
| 26.357 | 390.78 | 949.07 | 0.09860 | 0.10 |
| 23.668 | 390.77 | 924.70 | 0.09226 | 0.42 |
| 20.405 | 390.77 | 889.49 | 0.08461 | 0.37 |
| 18.896 | 390.74 | 870.39 | 0.08084 | 0.08 |
| 16.983 | 390.76 | 842.33 | 0.07519 | 0.26 |
| 15.498 | 390.77 | 816.72 | 0.07085 | 0.13 |
| 14.567 | 390.77 | 798.37 | 0.06792 | 0.23 |
| 13.206 | 390.78 | 767.22 | 0.06313 | 0.15 |
| 12.251 | 390.77 | 741.28 | 0.05949 | 0.23 |
| 11.488 | 390.78 | 717.12 | 0.05658 | 0.08 |
| 10.796 | 390.77 | 691.95 | 0.05333 | 0.10 |
| 10.212 | 390.77 | 667.31 | 0.05030 | 0.18 |
| 9.742 | 390.78 | 644.65 | 0.04829 | 0.14 |
| 9.349 | 390.80 | 623.29 | 0.04547 | 0.12 |
| 8.796 | 390.77 | 589.08 | 0.04209 | 0.24 |
| 8.473 | 390.78 | 566.13 | 0.04009 | 0.14 |
| 8.179 | 390.78 | 543.12 | 0.03782 | 0.14 |
| 7.907 | 390.77 | 520.02 | 0.03597 | 0.25 |
| 7.530 | 390.78 | 484.88 | 0.03344 | 0.17 |
| 7.085 | 390.78 | 439.85 | 0.03055 | 0.24 |
| 6.891 | 390.77 | 419.43 | 0.02947 | 0.17 |
| 6.693 | 390.76 | 398.42 | 0.02833 | 0.18 |
| 6.394 | 390.77 | 366.79 | 0.02655 | 0.23 |
| 6.194 | 390.79 | 345.99 | 0.02547 | 0.18 |

Table 2 (continued). Experimental Viscosities of the Mixture R-507A (0.5 R-143a + 0.5 R-125 by mass) as Measured in the Torsional Crystal Viscometer

The contents of each line represents the average of four measurements. The precision of the measurements is indicated by the relative standard deviation of the viscosity averaging, s_η/η . Calculated density values were obtained from REFPROP version 7.0.

| p | T | ρ | η | s_η/η |
|----------|----------|--------------------|----------|---------------|
| MPa | K | kg·m ⁻³ | mPa·s | % |
| measured | measured | calculated | measured | measured |
| 5.821 | 390.78 | 309.19 | 0.02382 | 0.21 |
| 5.618 | 390.77 | 290.29 | 0.02302 | 0.25 |
| 5.311 | 390.76 | 263.38 | 0.02190 | 0.20 |
| 5.103 | 390.78 | 246.19 | 0.02125 | 0.21 |
| 4.787 | 390.77 | 221.84 | 0.02044 | 0.33 |
| 4.502 | 390.77 | 201.58 | 0.01967 | 0.11 |
| 3.977 | 390.78 | 167.69 | 0.01887 | 0.73 |
| 3.604 | 390.78 | 146.03 | 0.01824 | 0.34 |
| 3.095 | 390.77 | 119.32 | 0.01764 | 0.39 |
| 2.668 | 390.79 | 98.901 | 0.01694 | 0.88 |
| 1.985 | 390.76 | 69.426 | 0.01652 | 0.29 |
| 1.551 | 390.78 | 52.455 | 0.01632 | 0.11 |
| 0.773 | 390.78 | 24.727 | 0.01594 | 0.26 |
| 0.6318 | 390.77 | 20.022 | 0.01596 | 0.05 |
| 0.3200 | 390.79 | 9.9350 | 0.01575 | 0.19 |
| 0.1608 | 390.78 | 4.9419 | 0.01581 | 0.15 |
| 52.104 | 420.82 | 1034.9 | 0.1249 | 0.35 |
| 40.738 | 420.88 | 977.48 | 0.1061 | 0.32 |
| 34.770 | 420.90 | 938.77 | 0.09624 | 0.36 |
| 34.756 | 420.89 | 938.68 | 0.09674 | 0.25 |
| 27.811 | 420.91 | 880.72 | 0.08310 | 0.16 |
| 23.853 | 420.90 | 837.62 | 0.07455 | 0.11 |
| 20.411 | 420.89 | 790.14 | 0.06668 | 0.21 |
| 17.528 | 420.92 | 738.77 | 0.05946 | 0.13 |
| 15.087 | 420.91 | 682.13 | 0.05246 | 0.13 |
| 13.329 | 420.90 | 629.42 | 0.04653 | 0.26 |
| 12.333 | 420.90 | 593.22 | 0.04301 | 0.13 |
| 11.104 | 420.92 | 540.15 | 0.03883 | 0.12 |
| 10.076 | 420.92 | 487.70 | 0.03450 | 0.30 |
| 9.291 | 420.90 | 442.74 | 0.03162 | 0.17 |
| 8.392 | 420.93 | 387.13 | 0.02872 | 0.27 |
| 7.574 | 420.92 | 335.38 | 0.02636 | 0.11 |
| 6.793 | 420.92 | 287.12 | 0.02406 | 0.12 |
| 6.098 | 420.92 | 246.39 | 0.02266 | 0.03 |
| 5.122 | 420.92 | 193.98 | 0.02077 | 0.52 |

Table 2 (continued). Experimental Viscosities of the Mixture R-507A (0.5 R-143a + 0.5 R-125 by mass) as Measured in the Torsional Crystal Viscometer

The contents of each line represents the average of four measurements. The precision of the measurements is indicated by the relative standard deviation of the viscosity averaging, s_η/η . Calculated density values were obtained from REFPROP version 7.0.

| p | T | ρ | η | s_η/η |
|----------|----------|--------------------|----------|---------------|
| MPa | K | kg·m ⁻³ | mPa·s | % |
| measured | measured | calculated | measured | measured |
| 3.907 | 420.91 | 136.79 | 0.01930 | 0.20 |
| 2.840 | 420.93 | 93.191 | 0.01854 | 0.24 |
| 1.609 | 420.93 | 49.283 | 0.01789 | 0.07 |
| 0.731 | 420.92 | 21.401 | 0.01735 | 0.10 |
| 0.3328 | 420.91 | 9.5524 | 0.01774 | 0.08 |
| 0.0898 | 420.91 | 2.5475 | 0.01858 | 0.08 |

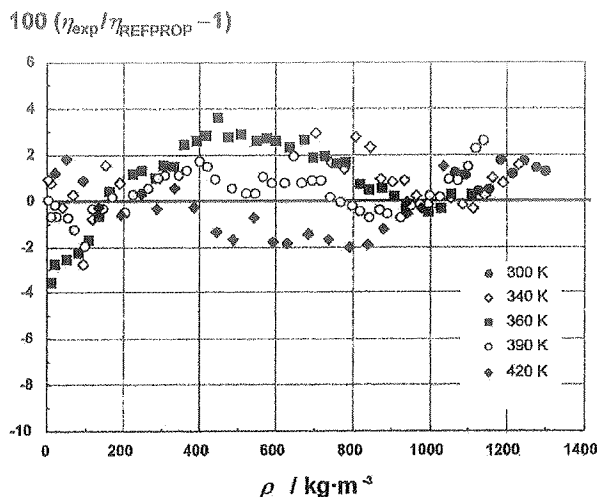


Figure 3 Percent deviations between experimental viscosities of the mixture R-507A (0.5 R-143a + 0.5 R-125 by mass) as measured in the torsional crystal viscometer and data calculated with the extended corresponding states model in REFPROP 7.0.

dence is revealed when the measured viscosities are compared with data that are calculated with the extended corresponding states model in NIST Standard Reference Database 23, REFPROP, version 7.0 (Lemmon et al. 2002). Figure 3 illustrates the percent deviations between experimental and calculated viscosities of R-507A. All range within $\pm 4\%$ and the majority of the deviations are within the estimated experimental uncertainty margin of $\pm 2\%$.

The present measurements constitute a significant improvement of our knowledge of the viscosity of R-507A. This is documented in Figure 4, which compares the previously available literature data of the binary system R-143a+R-125 with the extended corresponding states model in REFPROP. The saturated liquid measurements of Heide and Schenk (1996) deviate from the calculated viscosities between -4.5% and 15% . The gas measurements of Nabizadeh and Mayinger (1999) exhibit systematic deviations. They agree with the calculated data only in the limit of zero density and show increasing deviations up to 14% with increasing density. The surface light scattering measurements of Fröba et al. (2001) on saturated liquid R-507A deviate from the calculated data between -9.3% and 3.8% . In summary, all literature data for R-507A deviate from the calculated viscosities more than their estimated uncertainties. The present data agree with them within this margin, which suggests that the measurements of the literature data were affected by systematic errors.

Results for R-410A

Figure 5 shows the measured conductances G at 39 kHz of the blend R-410A as a function of density. As in R-507A,

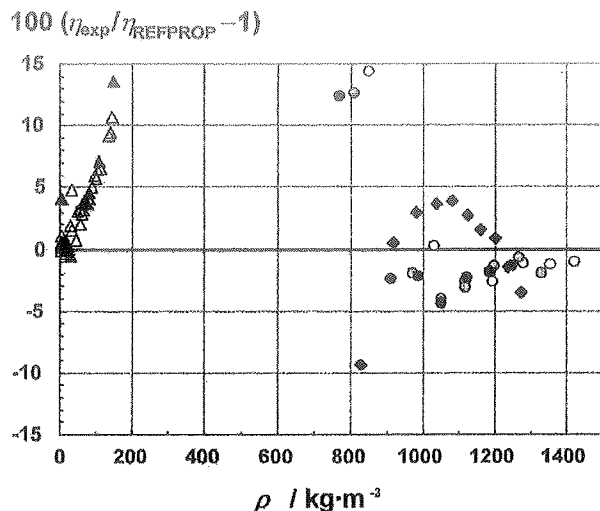


Figure 4 Percent deviations between literature data for the viscosity of the binary system R-143a + R-125 and data calculated with the extended corresponding states model in REFPROP 7.0.

Figure 4 Percent deviations between literature data for the viscosity of the binary system R-143a + R-125 and data calculated with the extended corresponding states model in REFPROP 7.0.

no conductance increase occurs in R-410A up to a density of about $500 \text{ kg}\cdot\text{m}^{-3}$. At higher densities, the conductances of R-410A contrast strongly with the low levels observed in R-507A (Figure 1). The density and temperature dependence are much more pronounced, and the highest measured conductance of $G = 5.72 \text{ }\mu\text{S}$ at 420 K and $1050 \text{ kg}\cdot\text{m}^{-3}$ is more than nine times higher than the highest conductance measured in R-507A. This observation is consistent with our previous studies of pure R-32 and of binary systems that contained R-32. Elevated electrical conductances were observed in all systems containing R-32, the reasons for which have not yet been identified in detail.

Based on molecular dynamics simulations, Lísal and Vacek (1996) suggested that the polar R-32 molecules associate in the liquid state via $\text{H}\cdots\text{F}$ hydrogen bonds. This was supported by the density functional theory calculations of Costa Cabral et al. (2001). It is not clear whether these associations are strong enough to enable electrical conduction via electron transport. However, the electrical conductances observed in our studies indicate the presence of a significant amount of charge carriers in fluids containing R-32. Sample contaminations with ionic impurities can be largely excluded as the reason for these conductances because our studies used samples that were independently prepared from various pure fluid samples, at different times and in different containers. Thus, the charge carriers are thought to originate from the R-32 itself by dissociation. Unfortunately, no other quantitative

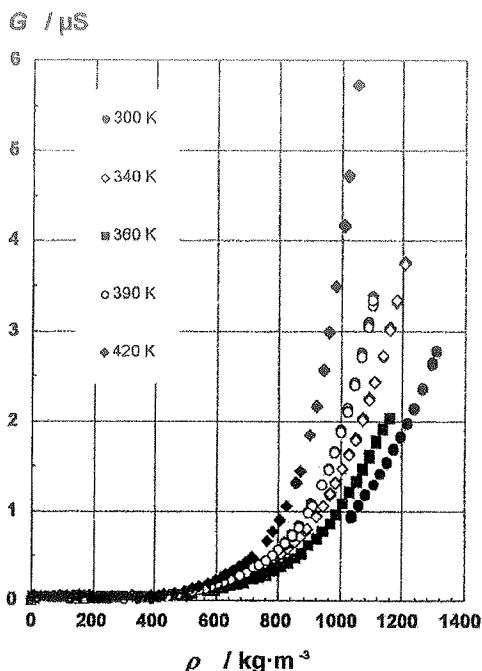


Figure 5 Conductances G at 39 kHz of the mixture R-410A (0.5 R-32 + 0.5 R-125 by mass) as measured in the torsional crystal viscometer.

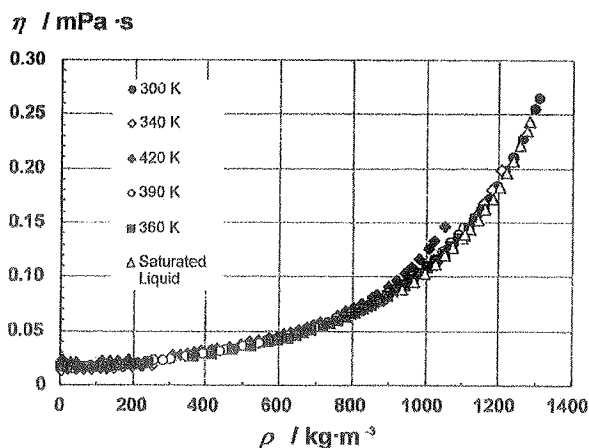


Figure 6 Density dependence of experimental viscosities of the mixture R-410A (0.5 R-32 + 0.5 R-125 by mass) as measured in the torsional crystal viscometer (isotherms) and in the sealed gravitational capillary viscometer (saturated liquid).

investigations have been carried out that would elucidate molecular interactions in fluids containing R-32. Barão et al. (1997) and Abbott et al. (1999) did measure permittivities of

hydrofluorocarbons including R-32. Both reports contain complete results only for the other compounds studied but not for R-32.

In conclusion, the elevated electrical conductances of R-410A that were measured in this work indicate the presence of charge carriers in the sample. The presence of polar molecules and charge carriers influences the operation of the torsional crystal viscometer on two counts. First, the molecules follow the applied ac voltage that is transmitted from the electrodes across the fluid sample to drive the torsional vibration of the piezoelectric crystal. Relaxation times of molecular reorientations on the order of picoseconds are much shorter than the period of the alternating voltage, which is in the millisecond range. Secondly, the molecules are alternately attracted and repelled by the oscillating surface charge of the piezoelectric crystal, which charge is generated by its torsional mechanical deformation. This generates a secondary flow perpendicular to the crystal surface that is superimposed on the primary shear flow of the sample fluid tangential to the crystal surface. The secondary flow adds an electroviscous component to the friction in the fluid that increases with the density of the fluid. Consequently, viscosities measured with the torsional crystal viscometer on polar and electrically conducting fluids are systematically higher than viscosities measured in instruments where the sample is not exposed to an alternating electric field.

The viscosities measured in the torsional crystal viscometer are tabulated in Table 3. Their density dependence is displayed in Figure 6. To corroborate these results, the viscosity of saturated liquid R-410A was measured for comparison in a sealed gravitational capillary viscometer between 242 K and 310 K. This instrument was described in detail by Laesecke et al. (1999). The viscometer was recalibrated by measurements of toluene at 320, 335, and 350 K. The calibration constant was obtained as $C_1 = (6.277 \pm 0.067) \cdot 10^{-12} \text{ m}^3 \cdot \text{s}^{-2}$. This value is consistent with our earlier calibrations (Laesecke and Hafer 1998; Laesecke et al. 1999). The data analysis of the R-410A measurements was based on the measured bulk density $\rho_{\text{bulk}} = 343.4 \text{ kg} \cdot \text{m}^{-3}$ of the sample in the viscometer. The contribution of the uncertainty of the bulk density to the experimental uncertainty of the viscosity measurements was assessed by comparing the calculated sample properties at the measured bulk density with those at bulk densities 10% below and above that value. The resulting variations in the saturated liquid and vapor density ranged from -0.014% to 0.017% and from -0.055% to 0.067%, respectively. Thus, the data analysis is rather insensitive to the uncertainty of the bulk density. The expanded uncertainty of the present measurements is estimated at $\pm 2.4\%$ (coverage factor of 2), the same level as in our previous measurements of the similar system R-32 + R134a (Laesecke and Hafer 1998). The results from the capillary viscometer are presented in Table 4 and included in Figure 6.

The temperature dependence of the viscosity of R-410A is more noticeable than in the results for R-507A. A magnified

**Table 3 . Experimental Viscosities of the Mixture R-410A (0.5 R-32 + 0.5 R-125 by mass)
as Measured in the Torsional Crystal Viscometer.**

The contents of each line represents the average of four measurements. The precision of the measurements is indicated by the relative standard deviation of the viscosity averaging, s_{η}/η . Calculated density values were obtained from REFPROP version 7.0. Values in *italic* not to be used in model development (see text).

| p | T | ρ | η | s_{η}/η |
|---------------|---------------|--------------------|----------------|-----------------|
| MPa | K | kg·m ⁻³ | mPa·s | % |
| measured | measured | calculated | measured | measured |
| <i>82.477</i> | <i>304.72</i> | <i>1309.7</i> | <i>0.2653</i> | <i>0.62</i> |
| <i>75.079</i> | <i>304.79</i> | <i>1296.5</i> | <i>0.2552</i> | <i>0.45</i> |
| <i>59.368</i> | <i>304.80</i> | <i>1265.1</i> | <i>0.2280</i> | <i>0.53</i> |
| <i>48.136</i> | <i>304.84</i> | <i>1238.8</i> | <i>0.2104</i> | <i>0.67</i> |
| <i>40.172</i> | <i>304.87</i> | <i>1217.5</i> | <i>0.1986</i> | <i>0.42</i> |
| <i>32.857</i> | <i>304.87</i> | <i>1195.3</i> | <i>0.1842</i> | <i>0.48</i> |
| <i>26.608</i> | <i>304.90</i> | <i>1173.6</i> | <i>0.1723</i> | <i>0.38</i> |
| <i>20.770</i> | <i>304.85</i> | <i>1150.5</i> | <i>0.1623</i> | <i>0.35</i> |
| <i>15.808</i> | <i>304.78</i> | <i>1127.7</i> | <i>0.1512</i> | <i>0.29</i> |
| <i>11.463</i> | <i>304.69</i> | <i>1104.2</i> | <i>0.1419</i> | <i>0.40</i> |
| <i>7.820</i> | <i>304.56</i> | <i>1080.9</i> | <i>0.1325</i> | <i>0.00</i> |
| <i>4.797</i> | <i>304.43</i> | <i>1057.5</i> | <i>0.1241</i> | <i>0.11</i> |
| <i>2.530</i> | <i>304.58</i> | <i>1034.4</i> | <i>0.1164</i> | <i>0.28</i> |
| <i>67.716</i> | <i>340.38</i> | <i>1208.1</i> | <i>0.1987</i> | <i>0.22</i> |
| <i>56.626</i> | <i>340.38</i> | <i>1179.3</i> | <i>0.1799</i> | <i>0.33</i> |
| <i>49.354</i> | <i>340.38</i> | <i>1157.7</i> | <i>0.1681</i> | <i>0.39</i> |
| <i>42.629</i> | <i>340.38</i> | <i>1135.1</i> | <i>0.1562</i> | <i>0.21</i> |
| <i>36.230</i> | <i>340.38</i> | <i>1110.6</i> | <i>0.1453</i> | <i>0.37</i> |
| <i>32.250</i> | <i>340.37</i> | <i>1093.4</i> | <i>0.1384</i> | <i>0.33</i> |
| <i>27.851</i> | <i>340.37</i> | <i>1071.9</i> | <i>0.1303</i> | <i>0.26</i> |
| <i>23.520</i> | <i>340.36</i> | <i>1047.6</i> | <i>0.1217</i> | <i>0.22</i> |
| <i>20.338</i> | <i>340.38</i> | <i>1026.8</i> | <i>0.1147</i> | <i>0.40</i> |
| <i>17.696</i> | <i>340.38</i> | <i>1007.0</i> | <i>0.1086</i> | <i>0.19</i> |
| <i>15.043</i> | <i>340.37</i> | <i>983.96</i> | <i>0.1026</i> | <i>0.25</i> |
| <i>13.208</i> | <i>340.36</i> | <i>965.38</i> | <i>0.09701</i> | <i>0.20</i> |
| <i>11.298</i> | <i>340.38</i> | <i>942.54</i> | <i>0.09143</i> | <i>0.39</i> |
| <i>9.774</i> | <i>340.40</i> | <i>920.65</i> | <i>0.08652</i> | <i>0.21</i> |
| <i>8.142</i> | <i>340.36</i> | <i>891.72</i> | <i>0.08004</i> | <i>0.33</i> |
| <i>7.200</i> | <i>340.38</i> | <i>870.20</i> | <i>0.07573</i> | <i>0.35</i> |
| <i>6.586</i> | <i>340.37</i> | <i>853.30</i> | <i>0.07263</i> | <i>0.10</i> |
| <i>5.930</i> | <i>340.37</i> | <i>830.95</i> | <i>0.06874</i> | <i>0.08</i> |
| <i>5.426</i> | <i>340.37</i> | <i>808.46</i> | <i>0.06573</i> | <i>0.11</i> |
| <i>4.398</i> | <i>340.38</i> | <i>250.68</i> | <i>0.01872</i> | <i>0.18</i> |
| <i>4.293</i> | <i>340.37</i> | <i>226.82</i> | <i>0.01792</i> | <i>0.26</i> |

**Table 3 (continued). Experimental Viscosities of the Mixture R-410A (0.5 R-32 + 0.5 R-125 by mass)
as Measured in the Torsional Crystal Viscometer.**

The contents of each line represents the average of four measurements. The precision of the measurements is indicated by the relative standard deviation of the viscosity averaging, s_η/η . Calculated density values were obtained from REFPROP version 7.0. Values in *italic* not to be used in model development (see text).

| p | T | ρ | η | s_η/η |
|----------------|---------------|--------------------|----------------|---------------|
| MPa | K | kg·m ⁻³ | mPa·s | % |
| measured | measured | calculated | measured | measured |
| <i>4.252</i> | <i>340.36</i> | <i>219.47</i> | <i>0.01769</i> | <i>0.20</i> |
| <i>4.102</i> | <i>340.37</i> | <i>196.94</i> | <i>0.01711</i> | <i>0.39</i> |
| <i>3.884</i> | <i>340.40</i> | <i>172.26</i> | <i>0.01660</i> | <i>0.41</i> |
| <i>3.583</i> | <i>340.38</i> | <i>146.26</i> | <i>0.01613</i> | <i>0.84</i> |
| <i>3.341</i> | <i>340.39</i> | <i>129.04</i> | <i>0.01573</i> | <i>0.44</i> |
| <i>3.007</i> | <i>340.37</i> | <i>108.97</i> | <i>0.01533</i> | <i>0.46</i> |
| <i>2.586</i> | <i>340.36</i> | <i>87.494</i> | <i>0.01508</i> | <i>0.26</i> |
| <i>2.084</i> | <i>340.37</i> | <i>65.815</i> | <i>0.01476</i> | <i>0.06</i> |
| <i>1.538</i> | <i>340.38</i> | <i>45.530</i> | <i>0.01460</i> | <i>0.09</i> |
| <i>0.792</i> | <i>340.38</i> | <i>21.762</i> | <i>0.01428</i> | <i>0.07</i> |
| <i>0.2873</i> | <i>340.39</i> | <i>7.5456</i> | <i>0.01417</i> | <i>0.05</i> |
| <i>0.21081</i> | <i>340.39</i> | <i>5.5011</i> | <i>0.01401</i> | <i>0.04</i> |
| <i>0.14055</i> | <i>340.38</i> | <i>3.6463</i> | <i>0.01392</i> | <i>0.05</i> |
| <i>0.08997</i> | <i>340.38</i> | <i>2.3243</i> | <i>0.01358</i> | <i>0.12</i> |
| <i>69.035</i> | <i>420.81</i> | <i>1051.9</i> | <i>0.1460</i> | <i>0.47</i> |
| <i>61.517</i> | <i>420.80</i> | <i>1024.4</i> | <i>0.1336</i> | <i>0.64</i> |
| <i>57.384</i> | <i>420.83</i> | <i>1007.4</i> | <i>0.1257</i> | <i>0.17</i> |
| <i>52.044</i> | <i>420.82</i> | <i>983.27</i> | <i>0.1156</i> | <i>0.28</i> |
| <i>47.959</i> | <i>420.83</i> | <i>962.62</i> | <i>0.1087</i> | <i>0.39</i> |
| <i>44.321</i> | <i>420.80</i> | <i>942.32</i> | <i>0.1030</i> | <i>0.23</i> |
| <i>40.831</i> | <i>420.80</i> | <i>920.63</i> | <i>0.09690</i> | <i>0.27</i> |
| <i>37.785</i> | <i>420.79</i> | <i>899.53</i> | <i>0.09122</i> | <i>0.18</i> |
| <i>33.742</i> | <i>420.80</i> | <i>867.44</i> | <i>0.08374</i> | <i>0.08</i> |
| <i>32.400</i> | <i>420.82</i> | <i>855.48</i> | <i>0.08094</i> | <i>0.24</i> |
| <i>29.433</i> | <i>420.80</i> | <i>826.32</i> | <i>0.07537</i> | <i>0.35</i> |
| <i>27.495</i> | <i>420.80</i> | <i>804.59</i> | <i>0.07119</i> | <i>0.19</i> |
| <i>25.772</i> | <i>420.80</i> | <i>783.05</i> | <i>0.06757</i> | <i>0.09</i> |
| <i>24.254</i> | <i>420.80</i> | <i>761.94</i> | <i>0.06442</i> | <i>0.18</i> |
| <i>21.360</i> | <i>420.85</i> | <i>714.25</i> | <i>0.05805</i> | <i>0.20</i> |
| <i>20.297</i> | <i>420.83</i> | <i>693.78</i> | <i>0.05559</i> | <i>0.24</i> |
| <i>19.407</i> | <i>420.83</i> | <i>674.94</i> | <i>0.05310</i> | <i>0.19</i> |
| <i>18.478</i> | <i>420.85</i> | <i>653.31</i> | <i>0.05064</i> | <i>0.20</i> |
| <i>17.664</i> | <i>420.74</i> | <i>633.17</i> | <i>0.04877</i> | <i>0.11</i> |
| <i>17.043</i> | <i>420.79</i> | <i>615.86</i> | <i>0.04692</i> | <i>0.01</i> |
| <i>16.368</i> | <i>420.81</i> | <i>595.87</i> | <i>0.04531</i> | <i>0.51</i> |

Table 3 (continued). Experimental Viscosities of the Mixture R-410A (0.5 R-32 + 0.5 R-125 by mass) as Measured in the Torsional Crystal Viscometer.

The contents of each line represents the average of four measurements. The precision of the measurements is indicated by the relative standard deviation of the viscosity averaging, s_η/η . Calculated density values were obtained from REFPROP version 7.0. Values in *italic* not to be used in model development (see text).

| p | T | ρ | η | s_η/η |
|---------------|---------------|--------------------|----------------|---------------|
| MPa | K | kg·m ⁻³ | mPa·s | % |
| measured | measured | calculated | measured | measured |
| 15.678 | 420.81 | 573.87 | 0.04346 | 0.11 |
| 14.796 | 420.82 | 543.02 | 0.04123 | 0.23 |
| 14.209 | 420.82 | 520.74 | 0.03951 | 0.15 |
| 13.620 | 420.84 | 496.86 | 0.03766 | 0.08 |
| 12.842 | 420.79 | 463.59 | 0.03551 | 0.20 |
| 12.135 | 420.82 | 431.27 | 0.03330 | 0.28 |
| 11.861 | 420.80 | 418.45 | 0.03257 | 0.17 |
| 11.243 | 420.83 | 388.88 | 0.03092 | 0.11 |
| 10.848 | 420.81 | 369.97 | 0.02970 | 0.26 |
| 10.447 | 420.87 | 350.43 | 0.02906 | 0.18 |
| 10.040 | 420.85 | 331.03 | 0.02829 | 0.16 |
| 9.630 | 420.83 | 311.71 | 0.02724 | 0.08 |
| 6.697 | 420.84 | 187.06 | 0.02272 | 0.27 |
| 5.825 | 420.81 | 155.72 | 0.02178 | 0.33 |
| <i>5.247</i> | <i>420.82</i> | <i>136.34</i> | <i>0.02156</i> | <i>0.78</i> |
| <i>4.524</i> | <i>420.80</i> | <i>113.55</i> | <i>0.02122</i> | <i>0.21</i> |
| <i>1.910</i> | <i>420.94</i> | <i>42.675</i> | <i>0.02059</i> | <i>0.18</i> |
| <i>1.309</i> | <i>420.83</i> | <i>28.560</i> | <i>0.02046</i> | <i>0.21</i> |
| <i>0.3344</i> | <i>420.78</i> | <i>7.0253</i> | <i>0.02261</i> | <i>0.28</i> |
| 66.399 | 390.07 | 1103.1 | 0.1448 | 0.36 |
| 62.029 | 390.07 | 1088.9 | 0.1396 | 0.25 |
| 55.814 | 390.06 | 1066.8 | 0.1315 | 0.23 |
| 50.409 | 390.07 | 1045.2 | 0.1232 | 0.35 |
| 45.592 | 390.07 | 1023.7 | 0.1158 | 0.49 |
| 41.324 | 390.05 | 1002.4 | 0.1097 | 0.18 |
| 37.358 | 390.06 | 979.99 | 0.1037 | 0.27 |
| 34.150 | 390.05 | 959.68 | 0.09810 | 0.23 |
| 31.118 | 390.06 | 938.08 | 0.09298 | 0.09 |
| 27.281 | 390.06 | 906.29 | 0.08581 | 0.16 |
| 25.964 | 390.04 | 893.96 | 0.08408 | 0.34 |
| 23.307 | 390.06 | 865.76 | 0.07844 | 0.84 |
| 21.577 | 390.07 | 844.52 | 0.07415 | 0.54 |
| 19.956 | 390.05 | 821.97 | 0.07091 | 0.00 |
| 18.621 | 390.06 | 800.66 | 0.06762 | 0.16 |
| 17.481 | 390.05 | 780.16 | 0.06437 | 0.14 |

Table 3 (continued). Experimental Viscosities of the Mixture R-410A (0.5 R-32 + 0.5 R-125 by mass) as Measured in the Torsional Crystal Viscometer.

The contents of each line represents the average of four measurements. The precision of the measurements is indicated by the relative standard deviation of the viscosity averaging, s_η/η . Calculated density values were obtained from REFPROP version 7.0. Values in *italic* not to be used in model development (see text).

| P | T | ρ | η | s_η/η |
|----------|----------|--------------------|----------|---------------|
| MPa | K | kg·m ⁻³ | mPa·s | % |
| measured | measured | calculated | measured | measured |
| 16.424 | 390.08 | 758.38 | 0.06121 | 0.13 |
| 15.465 | 390.07 | 736.07 | 0.05823 | 0.19 |
| 14.865 | 390.04 | 720.53 | 0.05589 | 0.28 |
| 14.134 | 390.06 | 699.16 | 0.05354 | 0.29 |
| 13.459 | 390.04 | 676.99 | 0.05087 | 0.16 |
| 12.638 | 390.05 | 645.53 | 0.04777 | 0.38 |
| 12.150 | 390.05 | 624.03 | 0.04578 | 0.20 |
| 11.768 | 390.04 | 605.43 | 0.04396 | 0.15 |
| 11.388 | 390.06 | 584.92 | 0.04227 | 0.13 |
| 11.092 | 390.04 | 567.88 | 0.04084 | 0.02 |
| 10.704 | 390.05 | 543.20 | 0.03927 | 0.16 |
| 10.407 | 390.06 | 522.83 | 0.03792 | 0.13 |
| 10.109 | 390.04 | 501.27 | 0.03594 | 0.06 |
| 9.810 | 390.07 | 478.02 | 0.03415 | 0.18 |
| 9.508 | 390.05 | 453.89 | 0.03250 | 0.20 |
| 9.307 | 390.06 | 437.18 | 0.03134 | 0.01 |
| 9.026 | 390.05 | 413.82 | 0.03003 | 0.10 |
| 8.760 | 390.04 | 391.69 | 0.02874 | 0.23 |
| 8.497 | 390.06 | 369.86 | 0.02756 | 0.24 |
| 8.209 | 390.04 | 346.77 | 0.02650 | 0.15 |
| 7.621 | 390.05 | 302.04 | 0.02438 | 0.07 |
| 7.316 | 390.06 | 280.59 | 0.02338 | 0.18 |
| 6.966 | 390.06 | 257.48 | 0.02266 | 0.16 |
| 6.965 | 390.05 | 257.43 | 0.02265 | 0.20 |
| 6.644 | 390.05 | 237.61 | 0.02176 | 0.19 |
| 6.222 | 390.06 | 213.46 | 0.02089 | 0.16 |
| 5.810 | 390.06 | 191.74 | 0.02036 | 0.12 |
| 5.345 | 390.06 | 169.25 | 0.01981 | 0.19 |
| 4.845 | 390.05 | 147.12 | 0.01917 | 0.73 |
| 4.319 | 390.06 | 125.83 | 0.01897 | 0.35 |
| 3.758 | 390.06 | 105.02 | 0.01826 | 0.13 |
| 3.195 | 390.07 | 85.892 | 0.01799 | 1.66 |
| 2.449 | 390.07 | 62.748 | 0.01734 | 0.14 |
| 1.850 | 390.06 | 45.732 | 0.01702 | 0.11 |
| 0.923 | 390.06 | 21.660 | 0.01674 | 0.05 |

Table 3 (continued). Experimental Viscosities of the Mixture R-410A (0.5 R-32 + 0.5 R-125 by mass) as Measured in the Torsional Crystal Viscometer.

The contents of each line represents the average of four measurements. The precision of the measurements is indicated by the relative standard deviation of the viscosity averaging, s_η/η . Calculated density values were obtained from REFPROP version 7.0. Values in *italic* not to be used in model development (see text).

| P | T | ρ | η | s_η/η |
|----------|----------|--------------------|----------|---------------|
| MPa | K | kg·m ⁻³ | mPa·s | % |
| measured | measured | calculated | measured | measured |
| 0.4576 | 390.07 | 10.480 | 0.01680 | 0.14 |
| 64.452 | 360.70 | 1157.4 | 0.1616 | 0.30 |
| 57.805 | 360.69 | 1137.8 | 0.1538 | 0.17 |
| 51.370 | 360.69 | 1116.8 | 0.1451 | 0.20 |
| 44.930 | 360.70 | 1092.9 | 0.1355 | 0.43 |
| 39.975 | 360.71 | 1072.2 | 0.1286 | 0.22 |
| 35.473 | 360.69 | 1051.0 | 0.1215 | 0.31 |
| 31.282 | 360.71 | 1028.6 | 0.1145 | 0.35 |
| 27.730 | 360.71 | 1006.9 | 0.1090 | 0.20 |
| 24.575 | 360.71 | 984.91 | 0.1026 | 0.13 |
| 21.881 | 360.70 | 963.40 | 0.09713 | 0.07 |
| 19.499 | 360.71 | 941.36 | 0.09205 | 0.20 |
| 17.542 | 360.68 | 920.65 | 0.08773 | 0.16 |
| 15.641 | 360.69 | 896.96 | 0.08285 | 0.13 |
| 14.110 | 360.69 | 874.50 | 0.07792 | 0.46 |
| 12.857 | 360.70 | 852.82 | 0.07438 | 0.34 |
| 11.747 | 360.71 | 830.09 | 0.07045 | 0.22 |
| 10.811 | 360.70 | 807.26 | 0.06662 | 0.17 |
| 10.003 | 360.71 | 783.34 | 0.06261 | 0.31 |
| 9.338 | 360.69 | 759.97 | 0.05968 | 0.25 |
| 8.858 | 360.70 | 738.45 | 0.05708 | 0.19 |
| 8.857 | 360.70 | 738.43 | 0.05712 | 0.08 |
| 8.483 | 360.71 | 718.78 | 0.05473 | 0.06 |
| 8.020 | 360.71 | 688.74 | 0.05041 | 0.10 |
| 7.735 | 360.70 | 665.30 | 0.04886 | 0.08 |
| 7.545 | 360.69 | 646.49 | 0.04614 | 0.13 |
| 7.357 | 360.71 | 623.79 | 0.04393 | 0.16 |
| 7.162 | 360.69 | 595.94 | 0.04162 | 0.23 |
| 7.027 | 360.70 | 571.48 | 0.03934 | 0.26 |
| 6.804 | 360.70 | 523.29 | 0.03579 | 0.23 |
| 6.604 | 360.69 | 471.53 | 0.03251 | 0.52 |
| 6.403 | 360.69 | 417.71 | 0.02924 | 0.16 |
| 6.185 | 360.71 | 365.31 | 0.02617 | 0.19 |
| 6.181 | 360.71 | 364.26 | 0.02611 | 0.18 |
| 5.375 | 360.70 | 242.70 | 0.02059 | 0.21 |

Table 3 (continued). Experimental Viscosities of the Mixture R-410A (0.5 R-32 + 0.5 R-125 by mass) as Measured in the Torsional Crystal Viscometer.

The contents of each line represents the average of four measurements. The precision of the measurements is indicated by the relative standard deviation of the viscosity averaging, s_η/η . Calculated density values were obtained from REFPROP version 7.0. Values in *italic* not to be used in model development (see text).

| P | T | ρ | η | s_η/η |
|--------------|---------------|--------------------|----------------|---------------|
| MPa | K | kg·m ⁻³ | mPa·s | % |
| measured | measured | calculated | measured | measured |
| 5.145 | 360.71 | 220.10 | 0.01992 | 0.51 |
| 4.840 | 360.71 | 194.51 | 0.01925 | 0.17 |
| 4.581 | 360.70 | 175.76 | 0.01876 | 0.63 |
| 4.232 | 360.69 | 153.56 | 0.01811 | 0.44 |
| 3.769 | 360.71 | 128.10 | 0.01752 | 0.25 |
| <i>3.464</i> | <i>360.70</i> | <i>113.33</i> | <i>0.01751</i> | <i>0.21</i> |
| 2.976 | 360.70 | 92.144 | 0.01716 | 0.81 |
| 2.446 | 360.71 | 71.772 | 0.01704 | 0.40 |
| 1.836 | 360.71 | 50.966 | 0.01657 | 0.29 |
| 1.102 | 360.70 | 28.841 | 0.01608 | 0.17 |
| 0.2988 | 360.70 | 7.3779 | 0.01661 | 0.14 |
| 0.1489 | 360.71 | 3.6396 | 0.01652 | 0.14 |

Table 4. Experimental Viscosities of the Mixture R-410A (0.5 R-32 + 0.5 R-125 by mass) as Measured in the Sealed Gravitational Capillary Viscometer

The data are listed in the order of measurements. The entries of each line represent the average of four measurements. The precision of the measurements is indicated by the relative standard deviation of the viscosity average, s_η/η . Calculated density values were obtained from REFPROP version 7.0 by flash calculations for the measured mixture bulk density $\rho = 343.4 \text{ kg·m}^{-3}$.

| T | ρ_{SL} | ρ_{SV} | η | s_η/η |
|----------|--------------------|--------------------|----------|---------------|
| K | kg·m ⁻³ | kg·m ⁻³ | mPa·s | % |
| measured | calculated | calculated | measured | measured |
| 287.98 | 1109.1 | 47.67 | 0.1383 | 0.52 |
| 242.38 | 1283.3 | 10.07 | 0.2433 | 0.49 |
| 245.02 | 1274.4 | 11.16 | 0.2351 | 0.42 |
| 250.04 | 1257.0 | 13.50 | 0.2215 | 0.13 |
| 255.10 | 1239.2 | 16.24 | 0.2070 | 0.16 |
| 260.08 | 1221.2 | 19.36 | 0.1955 | 0.34 |
| 265.16 | 1202.3 | 23.03 | 0.1828 | 0.35 |
| 270.08 | 1183.4 | 27.13 | 0.1717 | 0.21 |
| 275.08 | 1163.7 | 31.89 | 0.1622 | 0.11 |
| 280.03 | 1143.4 | 37.30 | 0.1527 | 0.25 |
| 285.12 | 1121.7 | 43.67 | 0.1438 | 0.27 |
| 288.06 | 1108.8 | 47.78 | 0.1386 | 0.23 |
| 290.11 | 1099.6 | 50.85 | 0.1351 | 0.22 |
| 295.13 | 1076.2 | 59.17 | 0.1267 | 0.36 |
| 300.13 | 1051.7 | 68.73 | 0.1192 | 0.08 |
| 305.06 | 1026.0 | 79.63 | 0.1114 | 0.13 |
| 310.08 | 997.97 | 92.62 | 0.1032 | 0.17 |
| 288.04 | 1108.9 | 47.75 | 0.1386 | 0.23 |

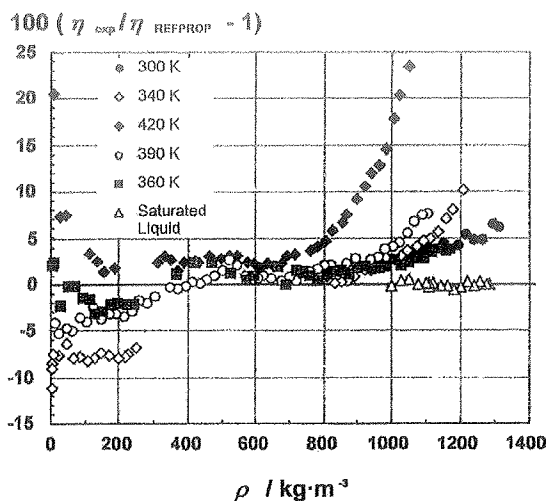


Figure 7 Percent deviations between experimental viscosities of the mixture R-410A (0.5 R-32 + 0.5 R-125 by mass) as measured in the torsional crystal viscometer (isotherms) and in the sealed gravitational capillary viscometer (saturated liquid) and data calculated with the extended corresponding states model in REFPROP 7.0.

view is offered in the deviation plot, Figure 7. Three density ranges can be distinguished. Mostly negative deviations from the model exist in the gas region below $300 \text{ kg}\cdot\text{m}^{-3}$. While the deviations at 340 K and at 390 K decrease monotonically with density to -5% and -9%, respectively, the results at 360 K and at 420 K exhibit a strong upswing in the limit of zero density. The trend at 340 K and at 390 K is consistent with the deviations of literature data from viscosities calculated with the extended corresponding states model in REFPROP, Figure 8, while the trend at 360 K and at 420 K is not.

The second density range extends from $300 \text{ kg}\cdot\text{m}^{-3}$ to $900 \text{ kg}\cdot\text{m}^{-3}$ for the isotherms 300 K to 390 K, while it is limited to $700 \text{ kg}\cdot\text{m}^{-3}$ at 420 K. Here the measured viscosities agree with the calculated values within their mutual estimated uncertainties.

At higher densities, the experimental results are systematically higher than the calculated values. The increase of the deviations corresponds to the increase of the electrical conductances, Figure 5, with respect to both density and temperature. Consequently, the experimental results represent the combined effect of molecular friction and electroviscous friction, but the working theory of the instrument accounts only for molecular friction. This is substantiated by the deviations of the results of the measurements in the capillary viscometer, which are included in Figure 7. They agree with the calculated data in the density range where the results of the torsional crystal viscometer deviate systematically.

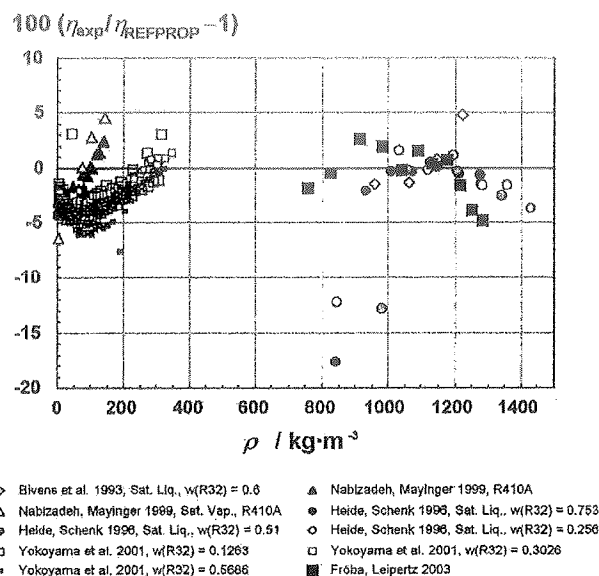


Figure 8 Percent deviations between literature data for the viscosity of the binary system R-32 + R-125 and data calculated with the extended corresponding states model in REFPROP 7.0.

Deviations of literature data for the viscosity of the binary system R-32+R-125 are shown in Figure 8 relative to data calculated with the extended corresponding states model in REFPROP. The first measurements of a mixture of 0.6 R-32 + 0.4 R-125 (by mass) with a reported uncertainty of $\pm 1.2\%$ were published by Bivens et al. (1993). Figure 8 shows agreement between these data and the predicted viscosities within the uncertainty estimate, except for the data point at 253.15 K, which deviates about 5%. Heide and Schenk (1996) measured three binary blends at mass fractions of R-32 of 0.753, 0.51, and 0.251 with a falling body viscometer. The uncertainty was reported to be $\pm 2\%$ for a viscosity of 0.2 mPa·s. This corresponds to the viscosity of saturated liquid R-410A at approximately 259 K. The results of Heide and Schenk do agree with the predicted viscosities within that margin and at such temperatures. However, the deviations increase to almost -4% at lower temperatures and to -18% at temperatures above 313 K. The surface light scattering measurements of Fröba and Leipertz (2003) on saturated liquid R-410A deviate from the calculated data between -5% and 3%. Two laboratories reported measurements in the gas region with oscillating disk viscometers. The results of Nabizadeh and Mayinger (1999) exhibit systematic density deviations similar to those of their data for R-507A, Figure 4, except the limiting value at zero density is offset by about -3%. Even higher deviations are displayed by their saturated vapor data, which were extrapolated. The appropriateness of the extrapolation method

appears questionable. On the other hand, their results are supported by the measurements of Yokoyama et al. (2001), which exhibit almost congruent deviations from the calculated viscosities. This agreement between independent results of two laboratories suggests that the extended corresponding states model in REFPROP does not capture correctly the molecular interactions in the binary system R-32+R-125.

The present work contributes a substantial number of new data that fill the existing data gap for this binary system in the density range from $300 \text{ kg}\cdot\text{m}^{-3}$ to $900 \text{ kg}\cdot\text{m}^{-3}$. Below $300 \text{ kg}\cdot\text{m}^{-3}$, the negative deviations are consistent with the results of the oscillating disk measurements of Nabizadeh and Mayinger (1999) and of Yokoyama et al. (2001). They will contribute to the refinement of the extended corresponding states model in REFPROP. Conversely, the results in the liquid and compressed liquid region (at densities above $900 \text{ kg}\cdot\text{m}^{-3}$ for the isotherms 300 K to 390 K and above $700 \text{ kg}\cdot\text{m}^{-3}$ at 420 K) form the basis to extend the working theory of the torsional crystal viscometer to highly polar and electrically conducting fluids.

CONCLUSIONS

Viscosity measurements of R-410A and R-507A have been carried out at sub- and supercritical temperatures to address some of the key data gaps for the properties of concern *vis a vis* the performance of refrigerant blends operating at extreme conditions. A torsional crystal viscometer was used that revealed not only viscous but also dielectric and conductive characteristics of the blends. The latter were about an order of magnitude more pronounced in R-410A than in R-507A which is due most likely to the presence of R-32. An electrical conductivity effect on the viscosities derived from the torsional crystal viscometer was corroborated by reference measurements with a sealed gravitational capillary viscometer where the test liquid is not exposed to an electric field. The new viscosity data fill wide gaps that existed in the literature data of both blends. Comparisons with the combined data indicate needs for further developments of models for the viscosity of mixtures at wide-ranging conditions.

ACKNOWLEDGMENTS

This work was sponsored by the Air-Conditioning and Refrigeration Technology Institute (ARTI) under their 21-CR program, the Building Equipment Division of the U.S. Department of Energy under contract number DE-AI01-97EE23775, and by the National Institute of Standards and Technology (NIST). Ralph Miller of the DuPont Company assisted in obtaining the high-purity R-32 and R-125 used in this work. Honeywell, Inc., donated the R-143a sample. The following NIST colleagues contributed to this work: Tom Bruno analyzed the mixture components and Mike Hiza prepared the mixtures. Collaboration with Marcia Huber, Eric Lemmon, and Mark McLinden is also gratefully acknowledged.

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