Viscosity of Fluorinated Propane Isomers. 2. Measurements of Three Compounds and Model Comparisons

Arno Laesecke* and Richard F. Hafer

National Institute of Standards and Technology, Physical and Chemical Properties Division, 325 Broadway, Boulder, Colorado 80303-3328

Viscosity data are reported for three fluorinated propane isomers in the saturated-liquid state over a combined temperature range from 248 to 348 K. The compounds are 1,1,1,3,3-pentafluoropropane (R245fa), 1,1,2,2,3-pentafluoropropane (R245ca), and 1,1,1,2,3,3,3-heptafluoropropane (R227ea). The measurements were carried out in sealed gravitational capillary viscometers. The estimated uncertainty of the measurements is ±3.4%. Including earlier viscosity measurements on 1,1,1,3,3,3-hexafluoropropane (R236fa) and 1,1,1,2,3,3,3-heptafluoropropane (R236ea), the viscosity data of all five fluids were correlated within their experimental uncertainty in terms of the rough hard-sphere model. The experimental data were also compared with predictions of the extended corresponding-states method in NIST Standard Reference Database 23 (REFPROP). Deviations range between –20 and 15%.

Introduction

Fluorinated propane derivatives are being examined as chlorine-free alternatives for trichlorofluoromethane (R11) and 1,2-dichlorotetrafluoroethane (R114), which serve as working fluids in vapor-compression systems at higher operating temperatures such as chillers (Smith et al., 1993). Augmenting previous measurements on two R236-isomers (Laesecke and Defibaugh, 1996), the viscosity of three more fluorinated propane compounds was investigated in this work. Their chemical names and ASHRAE designators are 1,1,1,3,3-pentafluoropropane (R245fa), 1,1,2,2,3-pentafluoropropane (R245ca), and 1,1,1,2,3,3,3-heptafluoropropane (R227ea).

Experimental Section

Chemicals. The R245fa sample was purchased from PCR, Inc. in Gainesville, FL, with a stated purity of 97% by mole. (To ensure that the experiments can be repeated exactly, it is occasionally necessary to identify commercial products by manufacturers' names or labels. In no instance does such identification imply endorsement by the National Institute of Standards and Technology, nor does it imply that the particular product or equipment is necessarily the best available for the purpose.) Qualitative gas chromatography/mass spectrometry analysis of the R245fa sample revealed the presence of 1,1,1,2,3-pentafluoropropane (CF₃CF=CF₂), an unidentifiable R245fa-isomer, and of a small amount of methyl bromide. R245ca was an experimental sample synthesized at Allied Signal Corp. The volume of sample (~4 mL) was just sufficient for measurements in the capillary viscometer. Therefore, qualitative gas chromatography/mass spectrometry analysis of the R245ca sample was carried out after the viscosity measurements by transferring the sample directly from the viscometer to the gas chromatograph. The analysis indicated 1,2-ethanediol as an impurity, possibly a residue from the bath, in which the viscometer was immersed during the measurements, that had formed in the high-pressure connection of the viscometer's filling valve. The R227ea sample was supplied by Great Lakes Chemical Corp. with a stated mass purity of 99.99%. Qualitative gas chromatography/mass spectrometry analysis confirmed the high purity as no impurities could be identified. The analyses were carried out qualitatively because some of the fluids were not included in the sample library for the calibration of the gas chromatograph. All fluids were used as received. They were condensed into the viscometers and degassed before the measurements.

Apparatus and Procedure. The normal boiling point temperatures of alternative refrigerants are below ambient temperature, which means that their vapor pressures at ambient temperature are higher than atmospheric pressure. Consequently, refrigerant viscometry requires sealed capillary viscometers to prevent the evaporation of the volatile samples during the measurements. The viscometers used in this work consist of two stainless steel reservoirs with sapphire windows. The reservoirs are connected in one viscometer by a straight vertical stainless steel capillary of length 1 = 148 mm and inner diameter d = 0.236 mm, while in the other viscometer a coiled capillary of length l = 480 mm and inner diameter d = 0.508 mm is used. The coiled capillary had an average coil diameter of D = 150 mm. The reservoirs of each viscometer are also connected by a stainless steel tube to return the liquid to the upper reservoir for a new measurement. The position h of the liquid–vapor interface in the upper reservoir is observed with a cathetometer and manually timed as the liquid drains through the capillary. The straight capillary viscometer has been used before with two fluorinated propane derivatives (Laesecke and Defibaugh, 1996) and three fluorinated ethane derivatives (Ripple and Matar, 1993). The pentafluoropropane isomers were measured in the coiled capillary viscometer because...
of their higher viscosity. R227ea has a much lower viscosity, and the efflux times in the coiled capillary viscometer became too short for accurate timing above 313 K. The liquid drained at this state in approximately 39 s over a level difference of 0.6 cm. Measurements with the straight capillary viscometer were therefore conducted with this fluid from 303 to 348 K.

The rate of fall of the interface, \( h \), is determined from the measurements. Together with the known cross sections of the upper reservoirs, \( A = 1.20 \times 10^{-4} \, \text{m}^2 \) for the straight capillary and \( A = 1.06 \times 10^{-4} \, \text{m}^2 \) for the coiled capillary viscometer, the volumetric flow rate of the liquid is obtained. The general working equation for both open and sealed gravitational capillary viscometers was derived by Wedlake (1979)

\[
\dot{\eta} = C_4 \left( (\rho_l - \rho_g) \frac{C_3}{H} - C_2 \rho_l h \right) + \sigma \frac{C_3}{H} \quad (1)
\]

Here \( \dot{\eta} \) is the viscosity of the liquid and \( \sigma \) is the surface tension.

The first term on the right side of eq 1 is the Hagen–Poiseuille term. The pressure, which causes the liquid to flow through the capillary, is equal to the apparent driving head minus pressure losses due to the effects of vapor buoyancy at the lower and upper liquid interfaces. Consequently, this term includes the difference between the saturated liquid and saturated vapor density \( \rho_l \) and \( \rho_v \). It should be noted that often quoted reviews on capillary viscometers discuss working equations that are applicable to open gravitational capillary viscometers when the vapor density is negligible. They do not mention the vapor buoyancy effect (Hardy, 1962; Kestin et al., 1973; Kawata et al., 1991), which can be appreciable. For example, the saturated-vapor density of R227ea at 348 K is 14% that of the liquid density. If that density is neglected, a 14% error in the measured viscosity would result.

Both viscometers were recalibrated because they had been completely disassembled for cleaning and for replacement of seals after being moved from their former location. The calibration fluid was a specially prepared toluene sample of 99.98% by mass purity, and the results of Kaiser et al. (1991) were used as reference data. Calibrations were carried out in the straight capillary viscometer at 323, 338, and 353 K, and from 250 to 340 K in the coiled capillary viscometer. The following values of the calibration constants \( C_1 \) in eq 1 were obtained

\[
C_1 = \begin{cases} 
(6.217 \pm 0.061) \times 10^{-12} \, \text{m}^3/\text{s}^2 & \text{for the straight capillary viscometer} \\
(2.430 \pm 0.031) \times 10^{-11} \, \text{m}^3/\text{s}^2 & \text{for the coiled capillary viscometer}
\end{cases}
\]

Calibration measurements were also attempted with pentane because it has a lower viscosity and surface tension than toluene. However, the results were inconsistent with the toluene calibrations suggesting a lack of standard reference data for the viscosity of pentane. This n-alkane was not included in a recent data evaluation of calibration liquids (Dymond and Øye, 1994) because (i) the available saturated liquid viscosity data for pentane were considered not as extensive as for other hydrocarbons and (ii) because its low boiling point limits the useful temperature range for calibrations of open viscometers. In sealed viscometers, such as employed in this work, the low boiling point of pentane is of no concern. Besides, further measurements of high accuracy have recently been published (Oliveira and Wakeham, 1992; Abdulagatov and Rasulov, 1996). Combined with earlier measurements the body of available data appears sufficient to establish standard reference viscosity data of pentane for calibrations. This work is now underway.

The second term in eq 1 is the Hagenbach–Couette correction for inertia and kinetic energy effects. The correction parameter \( C_2 \) is given by

\[
C_2 = \frac{m\alpha}{8\pi l} \quad (2)
\]

where the kinetic energy coefficient \( m \) depends on the fluid flow according to the empirical correlation \( m = 0.037(Re)^{1/2} \) (Cannon et al., 1960). The Reynolds number \( Re \) was approximated by

\[
Re = \frac{4A \rho_l \dot{\eta} h^2}{\pi \sigma (\rho_l - \rho_g) C_1} \quad (3)
\]

Values of the Reynolds number in the coiled capillary ranged from 18 to 137 for R245fa, from 8 to 92 for R245ca, and from 66 to 275 for R227ea. The measurements with R227ea in the straight vertical capillary viscometer resulted in Reynolds numbers between 142 and 330. Kinetic energy corrections were small in the present measurements, contributing at most 0.5% to the viscosity of R227ea at 348 K.

The third term in eq 1 is an approximate correction for surface tension effects, which reduce the hydrostatic head driving the liquid flow. Their magnitude depends on the capillary radius, the contact angle of the liquid at the reservoir wall, and the ratio \( \sigma (\rho_l - \rho_g)^{-1} \) (Wedlake et al., 1979). Using the surface tension correlation of Schmidt et al. (1996), the maximum of this ratio \( (15.3 \times 10^{-6} \, \text{m}^2/\text{s}^2) \) is found in the measurements for R245ca at 248 K. The associated relative reduction in the effective head is 0.4% according to Wedlake et al. R227ea exhibited a considerably lower surface tension than the two R245 isomers and the calibration fluid toluene. Hence, the surface tension difference between sample and calibration fluid is highest for R227ea, while the vapor pressure reduction due to the meniscus curvature is lowest. The opposite is true for the R245 isomers. Since these effects cancel each other and because of the small magnitude of the correction, it was not applied in the working eq 1 but included in the uncertainty estimate of the measurements.

The fourth correction in eq 1 is represented by parameter \( C_4 \). It accounts for the radial acceleration of the flowing liquid in viscometers with coiled capillaries. The correction is expressed in terms of the Dean number

\[
De = Re \frac{\sqrt{D}}{D} \quad (4)
\]

by the empirical correlation

\[
C_4 = 1 - \left[ 1 - \left( \frac{D_{De}}{De} \right)^{0.45} \right]^{11/0.45} \quad (5)
\]

as proposed by White (1929). Here, \( Re \) is the Reynolds number according to eq 3, \( D \) is the inner diameter of the capillary, and \( D \) is the diameter of the capillary coil. If the actual Dean number of a flow is less than the cutoff Dean number \( D_{De} \), then \( C_4 = 1 \). Comparing measurements in straight and curved tubes, White concluded that no correction was needed for Dean numbers less than \( D_{De} =
The data of Tables 1–4 are available in electronic format via anonymous ftp from host “ftp.boulder.nist.gov” in directory “pubb/fluids/NIST_Data/Viscosity/Capillary”.

11.6. Dawe (1973) summarized later investigations and suggested \( \text{De} = 6 \), which leads to considerably higher corrections. The maximum Dean number in the present measurements is 16.0 for R227ea at 313 K. Under these conditions the difference between the correction of Dawe and that of White is 9%. A comparison between the R227ea measurements with both viscometers at the overlapping temperatures 303, 308, and 313 K shows that the data from the instrument with the coiled capillary tend to be up to 2.5% higher than those from the straight vertical viscometer if the correction according to White is applied. Apparently, this correction should become effective at a lower Dean number. Better agreement between the R227 results from the two instruments would be achieved with a cutoff Dean number of \( \text{De} = 9.3 \), which is still considerably higher than \( \text{De} = 6 \) as suggested by Dawe. Since the difference in the viscosity data stemming from a change of \( \text{De} \) from 11.6 to 9.3 is within the estimated uncertainty of the measurements, the radial acceleration correction was applied as originally proposed by White. It affects only the R227ea measurements at 298 K and above.

Another error in the measured flow rate arises from a drainage film, which adheres to the inside walls and windows of the upper reservoir after inverting a viscometer to return the liquid for a new run. The lifting effect of such drainage films reduces the driving pressure head, thus increasing the efflux time (van Rossum, 1958). It depends on the density, viscosity, and surface tension of the liquid. A correction for this effect was not employed, but it was included in the uncertainty estimate below with a type B uncertainty margin of 1.5%.

The viscometers were immersed in a well-insulated, continuously stirred 75 L bath of ethylene glycol + water, whose temperature was maintained with a circulator and an external precision temperature controller. The temperature was measured with a platinum resistance thermometer (PRT) calibrated according to ITS-90 and accurate to \( \pm 0.01 \) K. The combined uncertainty of the thermometer and that due to temperature gradients and fluctuations in the thermostat is estimated at \( \pm 0.02 \) K. By analysis with the rough hard-sphere model discussed below, this introduces a maximum uncertainty of \( \pm 0.04\% \) in the viscosity for R245ca at 248 K.

Saturated liquid and vapor density data are required to evaluate the viscosity from eqs 1–3. For the three fluids, the experimental results of Defibaugh et al. (1996) and Defibaugh and Moldover (1997) were interpolated for the saturated-liquid densities at the measurement temperature. The quoted experimental uncertainty of \( \pm 0.1\% \) in the liquid-phase density introduces an uncertainty of \( \pm 1\% \) in the R245ca viscosity results at 250 K. Saturated-vapor densities were calculated using the Carnahan–Starling–De Santis (CSD) model in NIST Standard Reference Database 23 (Huber et al., 1995). The CSD-model was compared with the extended corresponding-states (ECS) model to approximate the uncertainty in vapor density. A maximum deviation of 5% occurred for R227ea at 348 K. This introduces an uncertainty of \( \pm 0.8\% \) in the viscosity at this temperature.

The total expanded uncertainty of the present measurements is estimated to be \( \pm 3.4\% \) with a coverage factor \( k = 2 \) (Taylor and Kuyatt, 1994). This estimate includes a type A uncertainty of 1% representing the precision of the instruments. Type B uncertainties include those due to pressure head variations (0.9%), drainage film effects (1.5%), calibration (2.4%), and kinetic energy correction (0.5%), as well as uncertainties of 1% and 0.8% due to the
saturated-liquid and saturated-vapor density data. The calibration and kinetic energy correction uncertainties are different from those of Ripple and Defibaugh (1997) because of a different cathetometer in the instrument setup and because of the different fluids that were measured in this work.

Results and Discussion

The experimental results for the saturated liquid viscosity of R245fa, R245ca, and R227ea are presented in Tables 1, 2, and 3, respectively. Figure 1 shows the measured viscosities of the three fluids in terms of reduced rather than absolute temperature because it is more suitable for comparison ($T_r = T/T_c$). Previously published results for the hexafluoropropane isomers R236ea and R236fa are also included (Laesecke and Defibaugh, 1996) as is the viscosity of the parent molecule propane. R245ca exhibits the highest viscosity among these five fluorinated propane derivatives, while R227ea and R236fa exhibit the lowest. All of them are considerably higher than the viscosity of propane. Experimental data by Schmidt et al. (1996) were used for the critical temperatures of four of the five fluids: 427.20 K for R245fa, 447.57 K for R245ca, 398.07 K for R236fa, and 412.45 K for R236ea. The critical temperature of R227ea (375.95 K) was measured by Beyerlein et al. (1993). No other experimental viscosity data for the fluorinated propane derivatives could be located in the literature.

Figure 1 shows also the saturated-liquid viscosity of chlorofluorcarbons R11 and R114, for which the fluorinated propanes are considered as substitute refrigerants. The experimental data by Kumagai and Takahashi (1991), corrected for the vapor buoyancy effect, are plotted. The viscosities of the fluorinated propanes are considerably higher than that of R11. On the other hand, the viscosity of R114 is closely matched by the viscosities of R236fa and R227ea.

Empirical correlations of saturated and compressed liquid viscosities of individual fluids are often formulated in terms of absolute or relative free volume (Batschinski, 1913; Hildebrand, 1971). Such correlations allow excellent data representation but have limited extrapolation capability.

In recent years, a number of successful correlations of dense-fluid transport properties has been based on the rough hard-sphere (RHS) model. Conceptually, this model is a refinement of the free-volume theories of Batschinski and Hildebrand since it is based on the application of kinetic theory of a dense fluid of smooth hard spheres to the van der Waals model of a liquid (Dymond, 1974). Further extending the model, Chandler (1975) showed that the transport coefficients of rough hard spheres are proportional to those of smooth hard spheres. The proportionality factor characterizes the degree of coupling between momentum transfer due to translational and rotational motions. For nonspherical molecules the pro-

![Table 2. Experimental Viscosities for Saturated Liquid R245ca](image)
portionality factor is called the roughness factor and is considered a measure for the influence of nonspherical shape on the transport properties of such fluids. The modified rough hard-sphere model was applied by Assael et al. (1992a–e, 1994, 1995) to the transport properties of many different fluids such as paraffinic and aromatic hydrocarbons, alcohols, and methane- and ethane-derived refrigerants. Most recently, Bleazard and Teja (1996) presented parameter tables for the viscosity and thermal conductivity of 58 polar liquids.

In view of the successful application of the rough hard-sphere model, it was decided to use this method for the correlation of the present viscosity data for fluorinated propane derivatives. The experimental data were converted to reduced viscosities \( \eta^* \) according to

\[
\eta^* = 6.0349 \times 10^8 \frac{\eta}{\rho^{0.3}} \sqrt{\frac{M}{RT}} \tag{6}
\]

where \( \eta \) is the experimental viscosity in Pa·s, \( \rho \) the density in mol·m\(^{-3}\), \( M \) the molar mass in kg·mol\(^{-1}\), \( R \) = (8.314 711 ± 0.000 014) J·(mol·K\(^{-1}\))\(^{-1}\) the universal gas constant (Moldover et al., 1988), and \( T \) the absolute temperature in K. The constant on the right side of eq 6 carries the unit mol\(^{-1}\)·L. This reduced viscosity is considered that of a rough hard-sphere fluid and fitted to the reduced viscosity of a smooth hard-sphere fluid whose density dependence is represented by the empirical correlation

\[
\log_{10} \left( \frac{\eta^*}{R_\eta} \right) = 0.959 - \frac{9.263}{V_r} + \frac{71.038}{V_r^2} - \frac{301.902}{V_r^3} + \frac{797.690}{V_r^4} - \frac{1221.977}{V_r^5} + \frac{987.574}{V_r^6} - \frac{319.463}{V_r^7} \tag{7}
\]

The reduced volume is defined as \( V_r = \rho_0(T_0) \eta^* \), where \( \rho_0 \) is the temperature-dependent close-packed density in kg·m\(^{-3}\).

Adjustable parameters are the roughness factor \( R_\eta \) and those associated with the temperature dependence of the close-packed density \( \rho_0(T_0) \). \( R_\eta \) was fitted as a constant,
and $F_0$ was fitted as a linear function of reduced temperature $T_r$:

$$\rho_0 = \beta_1 + \beta_2 T_r$$  \hspace{1cm} (8)

This functional form turned out sufficient to represent the experimental data, which cover a limited temperature range. Quartic polynomials may be necessary to represent high-pressure viscosities over wide temperature ranges (Assael et al., 1995). $R_\eta$ was found to be sensitive to the functional form selected for $F_0$. The adjustable parameters $R_\eta$, $\beta_1$, and $\beta_2$ were determined for each fluid by nonlinear least-squares minimization using the NIST package ODRPACK (Boggs et al., 1992). The optimum parameter values and their standard deviations are listed in Table 4.

Figure 2 shows how the experimental viscosities of all five fluids, reduced by the fitted roughness factors $R_\eta$, match the smooth hard-sphere viscosity correlation given by eq 7. Percent deviations between experimental and correlated values are shown in Figure 3 for the fluids that have been measured in this work, R245fa, R245ca, and R227ea. Figure 4 shows those for the previously measured hexafluoropropane isomers R236fa and R236ea. All experimental data are represented within their estimated experimental uncertainty.

There are advantages in applying the rough hard-sphere model to the data. First, the model can be safely extrapolated beyond the experimental conditions to pressures and temperatures in refrigeration cycles. This is of particular advantage with respect to the viscosity increase at lower temperatures and higher densities, which is usually underestimated when empirical correlations are extrapolated. Extrapolations of the model far beyond the data range will carry higher uncertainties due to the limited temperature range of the measurements. Extrapolations will also become incorrect below $V_r = 1.1$ because eq 6

Table 4. Parameter Values and Statistics of the Rough Hard-Sphere Correlation, eq 6, for Saturated Liquid R245fa, R245ca, R227ea, R236fa, and R236ea ($s$ = Standard Deviation)

<table>
<thead>
<tr>
<th>Fluid, Formula</th>
<th>($R_\eta \pm s$)</th>
<th>($\beta_1 \pm s$) kg m$^{-3}$</th>
<th>($\beta_2 \pm s$) kg m$^{-3}$ K$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>R245fa, CF$_3$-CH$_2$-CF$_2$</td>
<td>1.131 ± 0.0437</td>
<td>1824 ± 30.0</td>
<td>571 ± 66.4</td>
</tr>
<tr>
<td>R245ca, CHF$_2$-CF$_2$-CH$_2$F</td>
<td>1.287 ± 0.0194</td>
<td>1775 ± 11.1</td>
<td>704 ± 25.5</td>
</tr>
<tr>
<td>R227ea, CF$_3$-CHF-CF$_3$</td>
<td>1.051 ± 0.0126</td>
<td>1995 ± 16.5</td>
<td>677 ± 31.4</td>
</tr>
<tr>
<td>R236fa, CF$_3$-CH$_2$-CF$_3$</td>
<td>0.909 ± 0.0347</td>
<td>2186 ± 36.2</td>
<td>154 ± 73.2</td>
</tr>
<tr>
<td>R236ea, CF$_3$-CHF-CF$_2$</td>
<td>1.026 ± 0.0473</td>
<td>2082 ± 44.0</td>
<td>374 ± 89.5</td>
</tr>
</tbody>
</table>

Figure 1. Experimental viscosity of saturated liquid R245fa, R245ca, R227ea, R236fa, and R236ea as a function of reduced temperature. The viscosities of R11, R114, and propane are shown for comparison. Data of Kumagai and Takahashi (1991) corrected for the vapor buoyancy effect.

Figure 2. Rough hard-sphere model correlation for R245fa, R245ca, R227ea, R236fa, and R236ea.
exhibits a viscosity maximum in that density range (Blezard and Teja, 1996). It has not been investigated what minimal amount of experimental data is necessary to establish the rough hard-sphere model for the entire fluid range of a substance. This would be useful to develop efficient measurement strategies.

The rough hard-sphere model should provide information about the degree of steric hindrance in a fluid, measured by the departure of the roughness factor $R_\eta$ from 1. The fitted $R_\eta$-values in Table 4 suggest that R245ca ($R_\eta = 1.287$) and R245fa ($R_\eta = 1.131$) are the roughest molecules. This corresponds to their respective viscosities but does not compare with the viscosities and roughness factors of the other three compounds, Figure 1. Possibly this is due to the limited temperature range of the present data, which influences the correlation of the close-packed density $\rho_0$ and in turn that of the roughness factor $R_\eta$. Varying the temperature dependent-terms of the close-packed density $\rho_0(T_r)$ can significantly affect the roughness factor. However, the roughness factor of R236fa ($R_\eta = 0.909$) was found stable against such variations. $R_\eta$-values less than 1 were also reported by Assael et al. (1992e) and by Blezard and Teja (1996), but the physical significance of such values is not conclusive.

The dominant method to predict transport properties of pure compounds and mixtures over wide ranges of fluid states is the extended corresponding-states (ECS) model as implemented in NIST Standard Reference Database 23 REFPROP (Huber et al., 1995). The ECS and the RHS model are similar procedures. Both require a reference fluid correlation and two structure-related parameters or shape factors. The ECS model gains its predictive capability for transport properties from the fact that the shape factors can be determined from thermodynamic data. On the other hand, the RHS model uses the smooth hard-sphere viscosity as reference that is accessible by measure-
ments of simple fluids and computer simulations. The ECS model is based on different reference fluids for different classes of compounds. Reference fluid formulations for the ECS model require both extensive measurements and empirical viscosity surface correlations that can be reliably extrapolated.

First viscosity measurements of fluids such as those reported here allow reliability tests of predictions with the ECS model. The experimental viscosities for R236ea and R236fa were previously compared with ECS predictions, and very satisfactory agreement was found (Laeaecke and Defibaugh, 1996). Such comparisons were also carried out for the new measurements of R245ca, R245fa, and R227ea using REFPROP version 5.05, in which the shape factors of the three fluids had been based only on thermodynamic property data (Defibaugh et al., 1996; Defibaugh and Moldover, 1997). Hence, the viscosity computations were completely predictive. This REFPROP version contained a revised viscosity formulation for the reference fluid R134a (Laeaecke, 1997). Results of the comparison are shown in Figure 5 as percent deviations vs reduced temperature. The best agreement is found for R245fa, where the experimental viscosities are lower than the predicted values with an almost constant offset of –2.5%. In contrast, the deviations of the R245ca and R227ea viscosities are systematic and substantially higher than the estimated uncertainty of the measurements. Deviations of up to 15% occur for R245ca with decreasing temperature, whereas the deviations for R227ea vary with increasing temperature from –20% to 4%. The experimental data of this work can be used to improve the ECS predictions for the measured compounds.

Acknowledgment

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Figure 5. Comparison of experimental viscosities for R245fa, R245ca, and R227ea with predicted values from the extended corresponding-states model in REFPROP, version 5.05.
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