

High-Pressure Viscosity Measurements of 1,1,1,2-Tetrafluoroethane

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Abstract Viscosity measurements have been carried out with a falling-cylinder instrument in the compressed liquid and supercritical regions of the hydrofluorocarbon 1,1,1,2-tetrafluoroethane (R134a). A highly pure sample was used. The measurement region at temperatures from 293.15 K to 438.15 K with pressures from 10 MPa to 400 MPa extends the existing data range substantially. With estimated uncertainties of 3.5 % for viscosity, the greater of 1 MPa or 0.5 % for pressure, and 0.4 K for temperature, the new results can be used to reconcile inconsistencies between literature data sets. They also provide a test of the extrapolation capability of existing viscosity correlations for this fluid and enable the development of a more accurate and wider ranging formulation.

Keywords 1,1,1,2-tetrafluoroethane · Compressed liquid · Falling-body viscometer · High pressure · *n*-octane · R134a · Supercritical · Viscosity

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1 Introduction

In response to the depletion of the stratospheric ozone layer, the hydrofluorocarbon 1,1,1,2-tetrafluoroethane ($\text{CF}_3\text{-CH}_2\text{F}$, CAS Registry Number: 811-97-2, henceforth denoted as R134a) was one of the first alternative working fluids identified as a chlorine-free viable replacement of chloro-fluorocarbons in heating, ventilating, and air conditioning systems [1]. The establishment of a fundamental equation of state for the Helmholtz energy of R134a by Tillner-Roth and Baehr [2] indicated that a broad and accurate knowledge of the thermodynamic properties of the compound had been achieved by 1994.

Determining the viscosity of R134a turned out to be more difficult. Measurement results published until 1992 for liquid R134a differed by up to 33 %. A round-robin project under the auspices of the former IUPAC Subcommittee on Transport Properties [3–5] did not identify the causes of the discrepancies [6]. They were elucidated in two NIST studies. First, Ripple and Defibaugh [7] pointed out in the context of their viscosity measurements of 1,1-difluoroethane (R152a), 1,1,1-trifluoroethane (R143a), and pentafluoroethane (R125) that some of the literature data obtained in sealed gravitational capillary viscometers were analyzed without accounting for the vapor buoyancy that becomes significant in such instruments. Ripple and Defibaugh quantified the influence of the vapor buoyancy for the liquids they had measured and showed that correcting for this effect leads to remarkable consistency between their experimental results and the originally deviating literature data. The influence of the vapor buoyancy was investigated further by Laesecke et al. [8] with measurements of R134a and R32 (difluoromethane, CH_2F_2). In addition, the effect of radial acceleration on flow in coiled capillaries was quantified and demonstrated to even exceed that of the vapor buoyancy at certain conditions.

Accounting for the vapor buoyancy in sealed instruments and for the radial acceleration in those with helically coiled capillaries reconciled all originally deviating viscosity measurements in gravitational capillary viscometers with the results measured with other instruments. Even the first viscosity data for R134a by Shankland et al. [9] could be reconciled, although they deviated originally by up to 33 % from those of Okubo et al. [10]. Since Shankland et al. had used the same sealed gravitational capillary viscometer as Phillips and Murphy [11, 12], the reconciliation of their data provided also the clue for the strong deviations of the latter results, which had been inexplicable for nearly three decades. Furthermore, the article of Laesecke et al. [8] prompted Kumagai and Yokoyama [13] to correct for the effect of vapor buoyancy on the viscosity data for eleven liquids that Kumagai and Takahashi had published in 1991 [14].

In 2003, Huber et al. [15] developed an improved correlation for the viscosity of R134a on the basis of the reconciled and corrected literature data. Shortly thereafter, Comuñas et al. [16] published new measurement results that were obtained with a falling-body viscometer between 293.15 K and 373.15 K and to pressures of 140 MPa, exceeding the highest previously measured pressure of 100 MPa [17]. Unaware of the data of Comuñas et al., Scalabrin et al. published in 2006 a correlation for the viscosity of R134a that was based on the unreconciled literature data and their measurement errors [18]. Figure 1 provides a comparison of the correlation of Huber et al. with

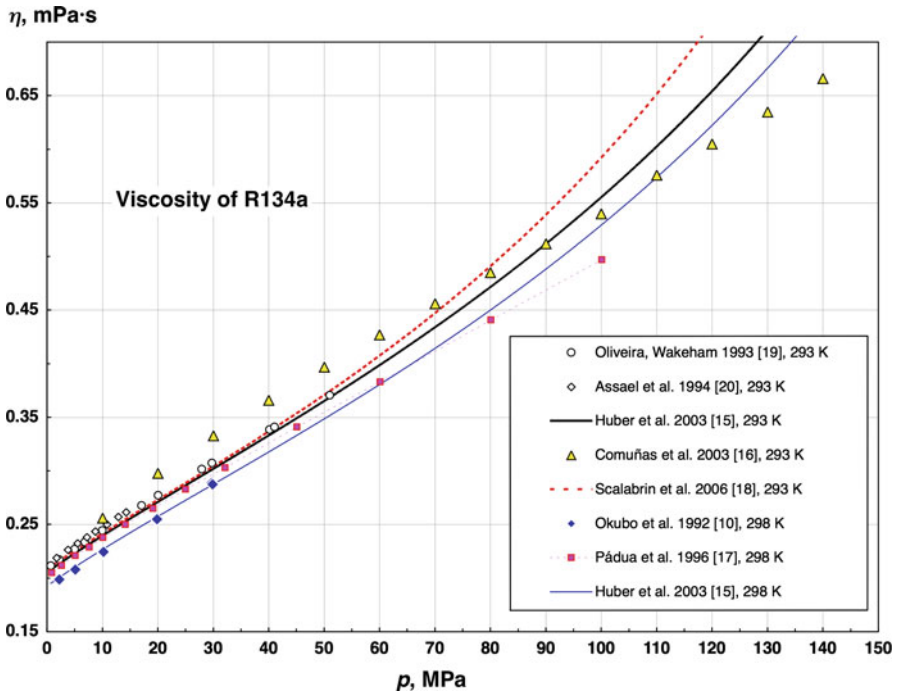


Fig. 1 Comparison of literature data and correlations for the viscosity of R134a at 293.15 K and at 298.15 K

the high-pressure data of Comuñas et al. at 293.15 K and with those of Pádua et al. at 298.15 K. At both temperatures the correlation extrapolates with a stronger viscosity-pressure dependence than that of the experimental data. The correlation of Scalabrin et al. shows a similar behavior, although it includes different temperatures and density terms than the correlation of Huber et al. At 293.15 K, calculated viscosities begin to exceed the measurement results of Comuñas et al. at 90 MPa, whereas at 298.15 K, the crossover occurs already at 60 MPa. At the same time, these two datasets appear inconsistent with other measurement results. At 293.15 K, the data of Comuñas et al. below 90 MPa are systematically higher than those of Oliveira and Wakeham [19] and Assael et al. [20], while at 298.15 K, the data of Pádua et al. [17] are systematically higher than those of Okubo et al. [10]. Consequently, additional viscosity measurements of R134a were needed to decide between the different viscosity-pressure dependencies of the correlations and the high-pressure data and to reconcile the inconsistencies between the experimental data.

This need motivated the measurements that are reported in this article. They were performed with a falling-cylinder viscometer along eight isotherms from 293.15 K to 438.15 K with pressures up to 400 MPa. The sample and its characterization are described in the next section, followed by a description of the instrument, its working theory, calibration, measurement protocol, and estimated uncertainty. Most of the 59 data points were measured at temperatures and/or pressures where no literature data

exist. Comparisons were made using the Ashurst-Hoover viscosity scaling concept and the Stickel analysis.

Besides the scientific interest in accurate knowledge of the viscosity of R134a, there is substantial need for viscosity data to high pressures in tribology. Many refrigeration compressors utilize sliding contacts between high modulus components with non-conformal geometry. For successful operation, these contacts rely mostly upon thin films of liquid under pressures of the order of 1 GPa [21]. The process fluid is a critical component to the reliability of compressors. The prediction and understanding of the film-forming capability of refrigerant/oil solutions requires a knowledge of the pressure dependence of viscosity of the process fluid at the operating pressure. No refrigerant has been characterized at such conditions before.

2 Experimental

2.1 Sample

For the measurements reported here, R134a in a 13.6 kg (30 lb) cylinder from a commercial manufacturer was analyzed at NIST-Boulder for water content by Karl–Fischer (KF) titration. Supply from this cylinder had been used previously in the viscosity measurements of Laesecke et al. with a sealed gravitational capillary viscometer [8]. The average of two titrations was 21.8 ppm water. The expanded ($k = 2$) uncertainty of KF titrations in this concentration range is 20 ppm. Therefore, the water concentration in the R134a was found to be (21.8 ± 20) ppm, which is at the detection limit of this method [22].

Sample from the vapor space of the supply cylinder was condensed into a stainless steel cylinder with a volume of 300 cm^3 that was evacuated to 10^{-7} mm Hg (1.3×10^{-5} Pa) and cooled with liquid nitrogen. The sample cylinder was then fully immersed into liquid nitrogen for about 2 h to freeze the R134a. While pumping a vacuum on the sample cylinder, the pressure leveled off at 3×10^{-5} mm Hg (0.004 Pa). After 30 min of pumping, the stainless-steel sample cylinder was returned to room temperature. This freezing and pumping cycle was repeated two more times with immersing the cylinder in liquid nitrogen for 2 h and pumping a vacuum for 30 min. In both cases the diffusion pump vacuum leveled off at 2×10^{-5} mm Hg (0.0027 Pa).

Subsequently, the vapor phase from the sample cylinder was analyzed by a gas chromatographic-mass spectrometric method. One peak was identified as 1,1,1,2-tetrafluoroethane. No other peaks were observed in the spectra.

2.2 Equation of State

The density of the sample liquid is needed to obtain the dynamic viscosity from the fall-time measurements in the falling-cylinder viscometer that was used in this study. Densities at the conditions of the present measurements were calculated with the fundamental equation of state for the Helmholtz energy of R134a by Tillner-Roth and Baehr [2]. The extrapolation behavior of this formulation beyond the maximum pressure of the experimental density data to which it was fitted (70 MPa) to pressures

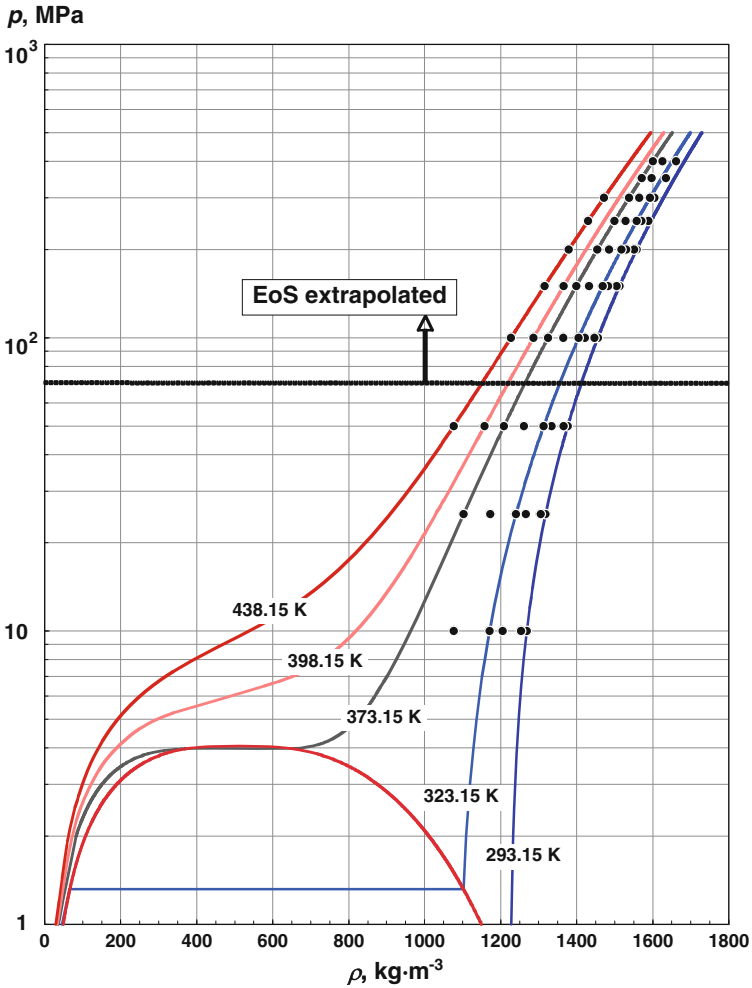


Fig. 2 Extrapolation behavior of the equation of state of Tillner-Roth and Baehr [2] in the temperature and pressure range of the present measurements

of 400 MPa is illustrated in the pressure, density diagram of Fig. 2 along five isotherms from 293.15 K to 438.15 K. The formulation extrapolates in a physically meaningful manner, although the associated increase of its estimated uncertainty of 0.05 % in the range covered by data is unknown. It was decided to use the densities calculated from the extrapolated Tillner-Roth and Baehr formulation in the analysis of the present viscosity measurements, because an uncertainty of 10 % in the calculated density would result in uncertainties of 1.6 % and 2.7 % in viscosity at the lowest and highest densities encountered in this study, $1076.55 \text{ kg} \cdot \text{m}^{-3}$ and $1661.55 \text{ kg} \cdot \text{m}^{-3}$, respectively. Considering the magnitude of these densities and given the meaningful extrapolation behavior of the formulation, the uncertainty of the calculated densities is likely to be significantly less than 10 %.

2.3 Viscometer

2.3.1 Instrument Description

The viscometer employed in this study is of the guided falling-cylinder type and has been described in [23,24]. The position of the magnetic sinker (AISI O1 tool steel) is continuously detected by a linear variable differential transformer (LVDT). The sinker falls within a non-magnetic cartridge (AISI 316 stainless steel) having a bore of 6.35 mm inside diameter, and this cartridge is contained within a non-magnetic pressure vessel. The LVDT (Schaevitz XSA-253) surrounds the entire assembly.¹ The sinker used in this study is of the “cup” style explained in [23], with an outside diameter of 6.17 mm, and is guided by four pads, 1 mm², arranged in a cruciform pattern about each end. The removable cartridge incorporates an o-ring sealed piston for volume compensation. This viscometer is a stress-controlled instrument, and the shear stress generated in the flow between the outside diameter of the sinker and the bore of the cartridge is 1.2 Pa.

The temperature of the vessel is maintained by the flow of heated air through slots placed between the shells of the composite pressure vessel. The temperature of the vessel is measured at the inner diameter adjacent to the cartridge at the axial position of the sinker with a type J thermocouple. The uncertainty of the measured temperature is estimated to be 0.4 K, and the temperature can be controlled to within 0.3 K of the target temperature.

Pressure is generated in a 10.6:1 intensifier using a hand pump for the low-pressure source. The intensifier is permanently attached to the viscometer, and they are rotated together to invert the viscometer for sinker reset. The high-pressure medium is di (2-ethylhexyl)sebacate, and the pressure of the medium is measured by a strain-gauge type transducer (Transmetrics P115BMI). The pressure uncertainty of the sample liquid, which includes the seal friction of the volume compensation piston, is estimated to be the greater of 1 MPa or 0.5 %.

The working equation for the viscometer is

$$\eta = C \left(1 - \frac{\rho}{\rho_s} \right) \Delta t, \quad (1)$$

where the mass density of the liquid and the sinker are ρ and ρ_s (7750 kg · m⁻³), respectively, and Δt is the time interval for the conditioned output from the LVDT to undergo a change of 100 mV near the terminal end of a fall. This change in signal, the measurement window, is equivalent to a displacement of the sinker of 0.87 mm. Because the sinker position is continuously detected, the window used for a measurement is arbitrary as long as the terminal velocity is reached. To improve repeatability for these measurements, an enlarged measurement window of 300 mV was utilized

¹ In order to describe materials and experimental procedures adequately, it is occasionally necessary to identify commercial products by manufacturers' names or labels. In no instance does such identification imply endorsement by the National Institute of Standards and Technology, or does it imply that the particular product or equipment is necessarily the best available for the purpose.

for all measurements. No correction was employed for the effect of pressure upon the working dimensions of the viscometer, and the effects of temperature on both the working dimensions of the viscometer and on the LVDT sensitivity are addressed in the temperature dependence of the calibration factor, C .

Modifications to the viscometer were necessary to be able to fill the cartridge with the required volume (1.3 mL) of R134a. Non-volatile liquids are simply injected through a hole in the volume-compensating piston. The trapped gas is withdrawn through the same hole, which is then sealed by a threaded plug. A new volume-compensating piston was fabricated with the plug replaced by a valve. A filling fixture was also manufactured that fixed the piston position in the cartridge during filling and that provided a manifold to evacuate the cartridge and deliver the sample liquid. The filling routine was as follows: the cartridge was evacuated to 2 cm Hg (2.7 kPa) followed by admitting sample vapor at the room-temperature saturation pressure. This was repeated four times. The cartridge was again evacuated and filled with liquid from a cylinder at 30 °C while the cartridge was maintained at 5 °C. The cartridge was then sealed with the valve and placed into the pressure vessel.

2.3.2 Calibration Check with Measurements of Viscosity Standards, *n*-octane and di(2-ethylhexyl)sebacate

Measurements and calibrations over the course of 9 years have shown that for this sinker the calibration factor $C = 1.84$ mPa is appropriate. No clear tendency for the temperature dependence of C has been observed for this particular sinker, although for similar sinkers made of AISI 430 stainless steel, C has been found to decrease with temperature. The modifications to the viscometer cartridge included the addition of a hardened steel valve pintle, which is magnetic. Therefore, it is possible that the proximity of this component to the magnetic sinker might have reduced the sensitivity of the LVDT.

The viscosities of two standard reference liquids from Cannon Instrument Comp., HT240 (lot 08101) and N2 (lot 10101), at ambient pressure were measured with the modified cartridge to check the calibration. The results are plotted in Fig. 3 as percent deviations versus temperature. The standard deviation of relative deviations between measurement results and certified reference values is 1.8 % in the temperature range from 293.15 K to 423.15 K.

Calibration measurements in the compressed-liquid region were carried out with *n*-octane (Fluka > 99.5 mol%) before the measurements of R134a and with di(2-ethylhexyl)sebacate (Fluka > 97 mol%) after the measurements with R134a. Reference viscosities measured with a vibrating wire viscometer are available for *n*-octane [25] for a wide range of temperatures and pressures to 200 MPa. Caudwell et al. compared their results with the correlation by Huber et al. [26], which was developed based on a critical review of the available literature data. Their results show an average absolute deviation of 0.6 % from the correlation of Huber et al. with a maximum deviation of 2.7 %. Target pressures of (0.1, 20, 100, and 200) MPa were chosen for comparisons in this study, and measurements were obtained at temperatures of (25, 50, 75, and 100) °C at pressures for which data are available close to the target pressures. The relative deviations of the present results for

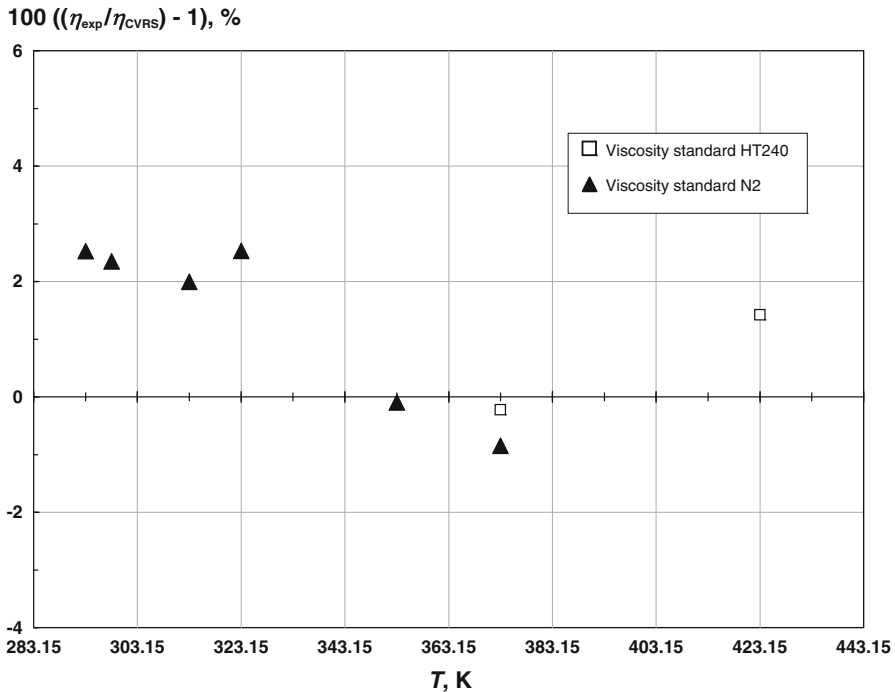


Fig. 3 Deviations of measured viscosities from certified viscosity reference standard (CVRS) values at ambient pressure

n-octane from the reference values of Caudwell et al. are shown versus pressure in Fig. 4. The standard deviation of relative deviations is 2.3 %. In view of these results, the calibration factor was employed unchanged from the historical value. We note that the first measurements of octane, made in the first test measurements with this configuration, resulted in fall time intervals that were 6 % larger than expected from the historical calibration. No explanation for this anomaly has been found.

After the R134a measurements, the performance of the viscometer was validated by measurements of di(2-ethylhexyl)sebacate (Fluka > 97 mol%) at 37.8 °C up to a pressure of 403 MPa. The percent deviations relative to the data that Novak and Winer had obtained in a capillary viscometer [27] are also shown in Fig. 4. The standard deviation of relative deviations is 1.6 %. This comparison confirmed the value of the calibration factor *C* for this sinker, too.

3 Results for the Viscosity of R134a

The viscosities of R134a resulting from the present measurements are listed in Table 1 and plotted in Fig. 5. They were obtained along eight isotherms from 293.15 K to 438.15 K with pressures from 10 MPa to 400 MPa. Their estimated uncertainty is 3.5 %. For fragile, glass-forming liquids such as diesters and higher molecular branched hydrocarbons, the general pressure dependence of viscosity follows a

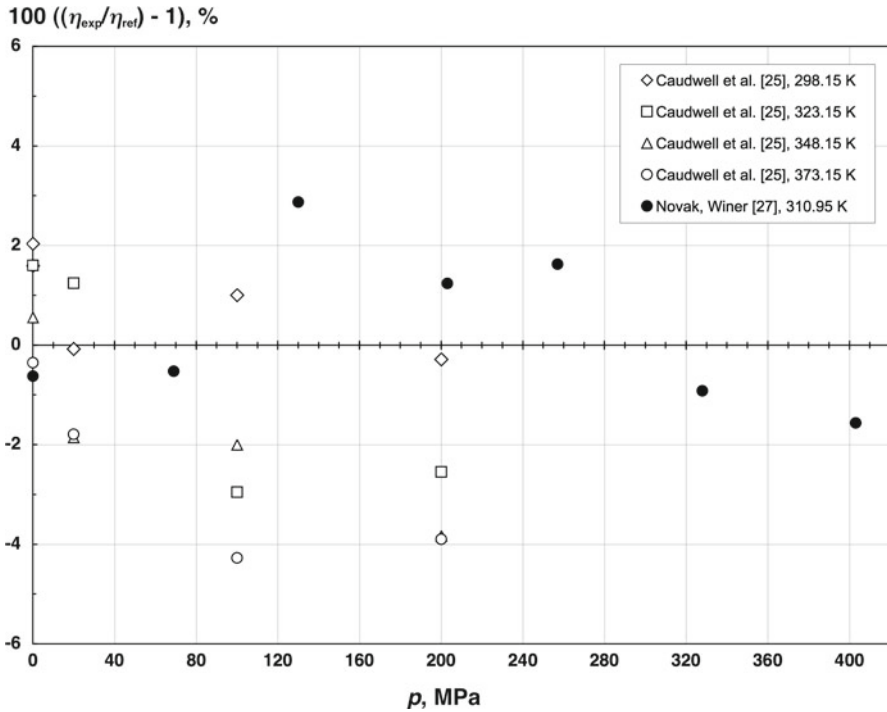


Fig. 4 Deviations of calibration measurements from the vibrating-wire viscometer measurements of Caudwell et al. [25] on *n*-octane to 202 MPa and from the capillary viscometer measurements of Novak and Winer [27] on di-(2-ethylhexyl) sebacate to 403 MPa

slower-than-exponential rule at low pressure, transitioning at an inflection point to faster-than-exponential response at greater pressure [28,29]. There is a minimum in $d(\ln \eta)/dp$ at each temperature. The present material responds to pressure in a very different manner. The pressure dependence is slower than linear at low pressure, transitioning at an inflection point to a faster-than-linear response at higher pressure. As shown in Fig. 6, there is a clear minimum in $d\eta/dp$ on the isotherms at 323.15 K, 348.15 K, 373.15 K, and 438.15 K. Differentiation of the data at the other temperatures results in scatter that does not resolve minima on these isotherms.

4 Viscosity Scaling

There are many methods to correlate the viscosity in terms of pressure or density and temperature [30]. In the compressed liquid region, free-volume terms have been applied successfully [24] but their divergence limits their suitability for extrapolations. A different approach is employed here which offers advantages in that respect.

In 1975, Ashurst and Hoover deduced on the basis of nonequilibrium molecular dynamics simulations of the Lennard-Jones potential [31] that viscosity may be expressed over a large part of the fluid region as a function of a single variable, $T V^{n/3}$,

Table 1 Viscosity data of 1,1,1,2-tetrafluoroethane (in mPa·s) measured in this study as a function of temperature and pressure

p (MPa)	Temperature T (K)							
	293.15	298.15	313.15	323.15	348.15	373.15	398.15	438.15
10	0.2550	0.2368	0.2070	0.1805	0.1405			
25	0.3008	0.2795	0.2461	0.2229	0.1783	0.1531		
50	0.3631	0.3435	0.3127	0.2852	0.2343	0.2038	0.1725	0.1458
100	0.5045	0.4988	0.4302	0.3946	0.3327	0.2931	0.2544	0.2131
150	0.6605	0.6459	0.5758	0.5020	0.4300	0.3764	0.3243	0.2789
200	0.8252	0.8190	0.7155	0.6252	0.5368	0.4649		0.3408
250		0.9773	0.8952	0.7651	0.6421	0.5564		0.3977
300			1.069	0.9140	0.7647	0.6468		0.4612
350			1.250		0.8894	0.7557		
400			1.446		1.040	0.8715		

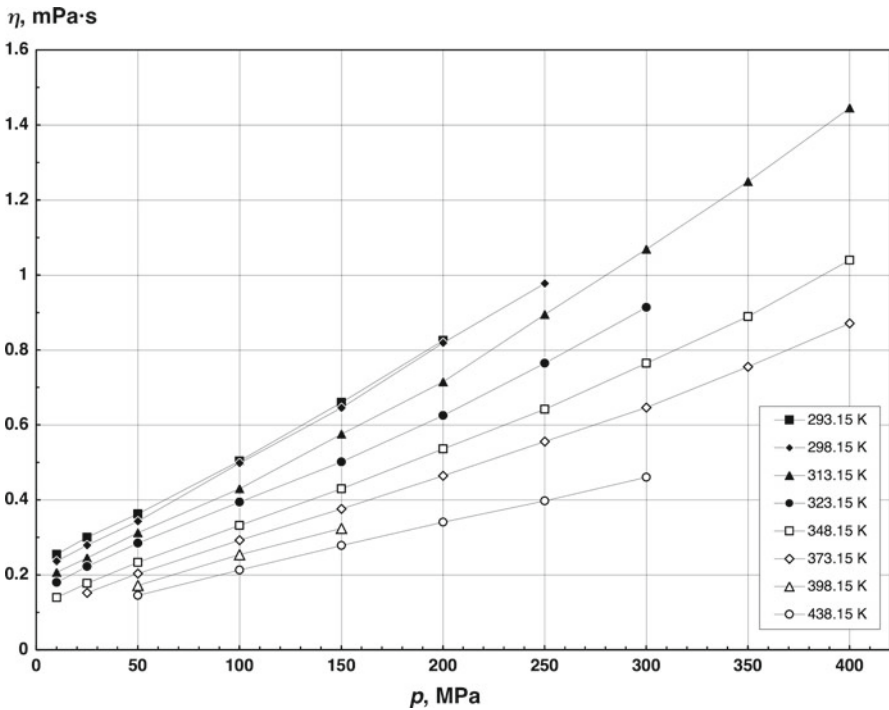


Fig. 5 Viscosity data of 1,1,1,2-tetrafluoroethane measured in this study as a function of pressure along isotherms. Lines are drawn to guide the eye of the viewer

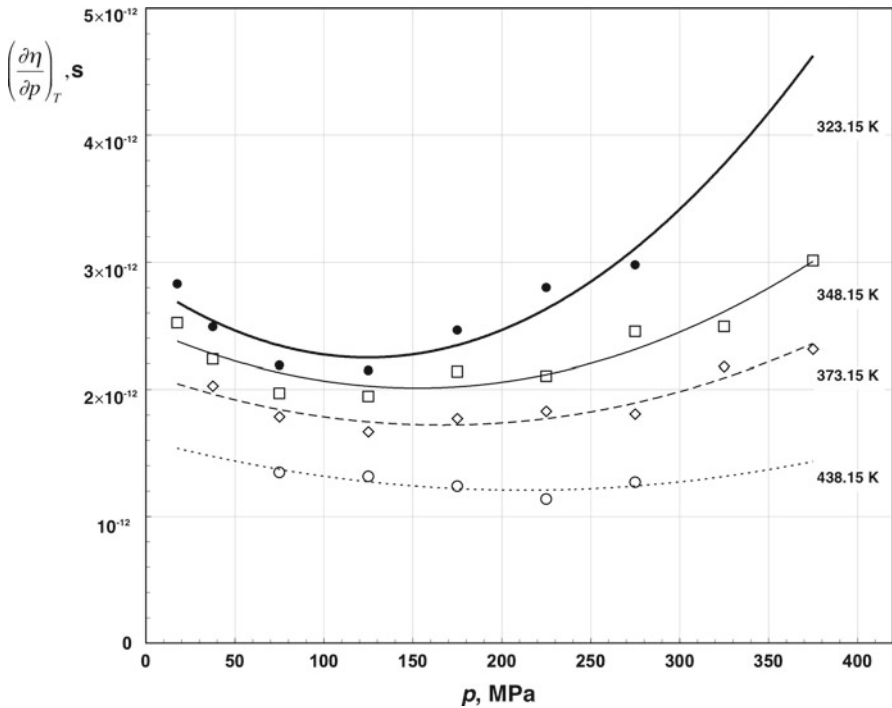


Fig. 6 Viscosity-pressure slope as a function of pressure indicating an inflection point in the viscosity-pressure dependence of R134a. Lines represent correlations of the isothermal data with quadratic polynomials

where n is the inverse n th power of the repulsive part of the potential ($n = 12$ for the Lennard-Jones potential). This scaling parameter may be conveniently written as

$$\varphi = (T/T_R) (\rho_R/\rho)^\gamma, \tag{2}$$

where T_R and ρ_R are the temperature and density, respectively, at a reference state. The interaction parameter, γ , has been experimentally determined for a number of liquids [32,33] and, with the exception of some hydrogen-bonded liquids, the viscosity can be written as a function of φ alone in the compressed liquid region, $\eta = F(\varphi)$.

This viscosity scaling rule has been applied to the present measurements. The reference state was chosen to be $T_R = 293.15$ K (20 °C) and $p = 10$ MPa ($\rho_R = 1.26884$ g · cm⁻³). With $\gamma = 12.84$, a plot of viscosity versus φ results in the compact master curve shown in Fig. 7. The Stickel analysis [34] is a non-model-specific test that investigates the behavior of the function of X ;

$$S(X) = \left(\frac{d \ln \eta}{d(X)} \right)^{-1/2}, \tag{3}$$

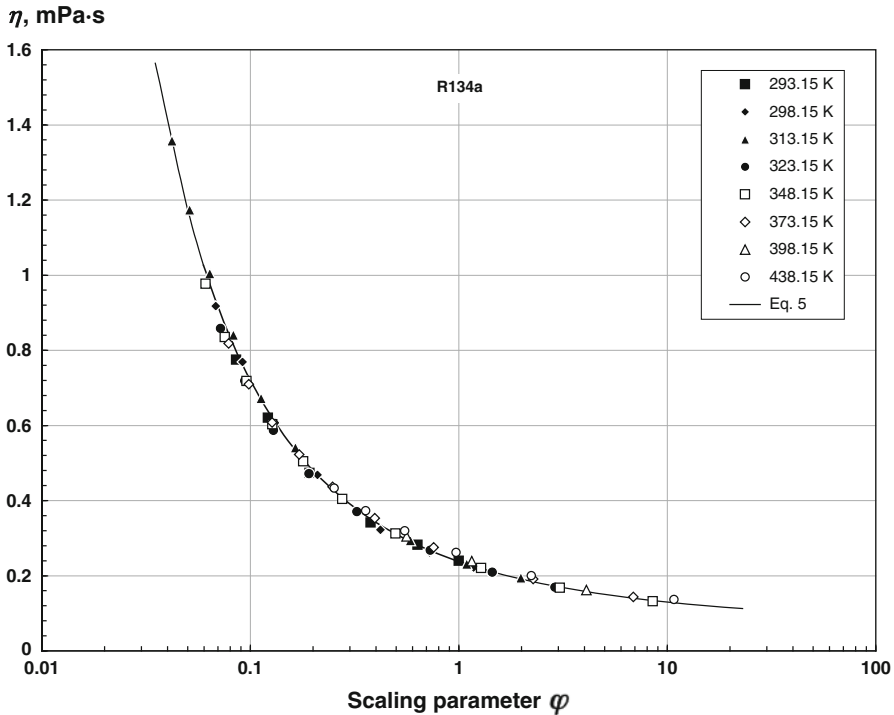


Fig. 7 Viscosity master curve with the scaled measurement results of this study

where X may represent pressure, reciprocal temperature, or, in this case, $1/\varphi$ [35,36]. The plot of S versus $1/\varphi$ is shown in Fig. 8 with a trend line fitted to the data for 313.15 K. This curve represents the function, $S = m(1/\varphi)^w$, where m and w are positive constants. Rearranging and integrating leads to the appropriate form of $\eta = F(\varphi)$ via

$$\ln \eta = \frac{1}{m^2(1-2w)} \left(\frac{1}{\varphi}\right)^{1-2w} + \text{constant}, \tag{4}$$

which can be reduced to

$$\eta = \eta_0 \exp \left[\frac{A}{\varphi^q} \right], \tag{5}$$

with $q = 1 - 2w$ and $1/A = qm^2$. For $q < 1$, Eq. 5 is the form suggested by Pensado et al. [33]. A least-squares regression provided the needed coefficients as $\eta_0 = 0.0672 \text{ mPa}\cdot\text{s}$, $A = 1.337$, and $q = 0.2405$ with a relative standard deviation of 3.0% in the viscosity. Equation 5 is plotted in Fig. 7 as the scaling function. Equation 5 exhibits the viscosity-pressure inflection at similar pressures as those shown in Fig. 6 and at all temperatures of the experimental data.

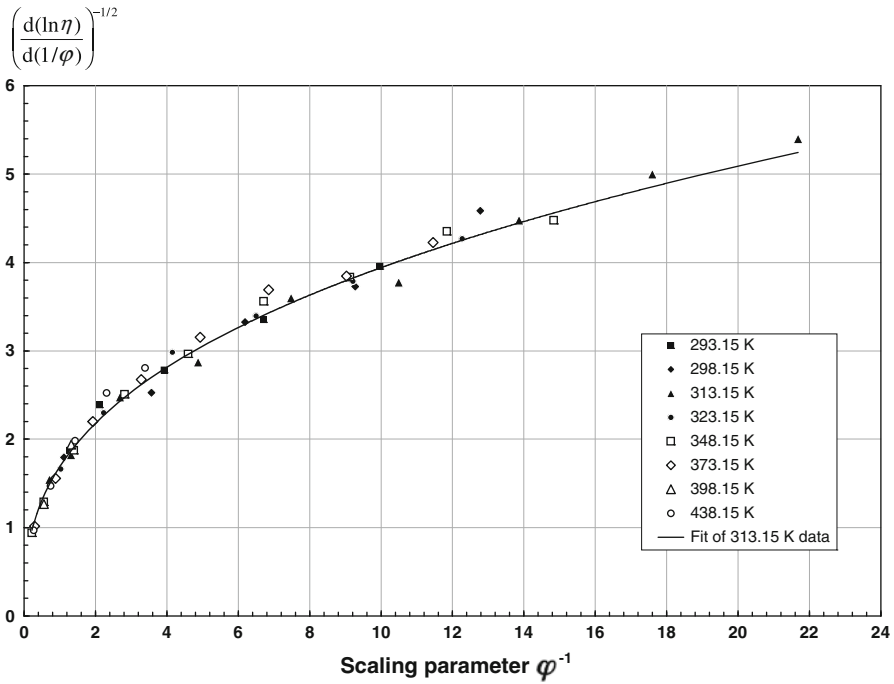


Fig. 8 Stickel analysis reveals the functional form of $\eta = F(\varphi)$

5 Comparison with Literature Data

The scaling function, Eq. 5, provides a reference to compare the measurement results of this study with viscosity data for compressed liquid R134a in the literature. Figure 9 shows the pressure-temperature range of the present measurements in context with a coverage of selected previous experimental studies of compressed liquid R134a that are considered reliable. This includes the measurements by Okubo et al. [10], Oliveira and Wakeham [19], Assael et al. [20], Pádua et al. [17, 37], and most recently, Comuñas et al. [16]. All of them overlap with the present measurements to some extent. Figure 9 includes also the data sets of Wilhelm and Vogel [38] and of Shibasaki-Kitagawa et al. [39] to indicate the extent to which the viscosity of R134a has been measured. Huber et al. [15] assessed the reliability of other data sets in more detail.

Figure 10 illustrates percent deviations versus pressure for the selected viscosity datasets and the present measurement results relative to values calculated with Eq. 5 as adjusted to the present results. The smallest deviations from the scaling function (<0.44 %) are obtained for the results of Pádua et al. at 248.20 K [17]. These measurements were carried out with a vibrating-wire viscometer with a reported uncertainty of 2.5 % at two more isotherms, 273.15 K and 298.11 K. They deviate below the scaling function by no more than -3 %. However, the saturated liquid viscosities that Pádua et al. reported in their second paper [37] deviate from the scaling function from -2.5 % to 28.7 %. The data that Assael et al. [20] measured with a vibrating-wire viscometer

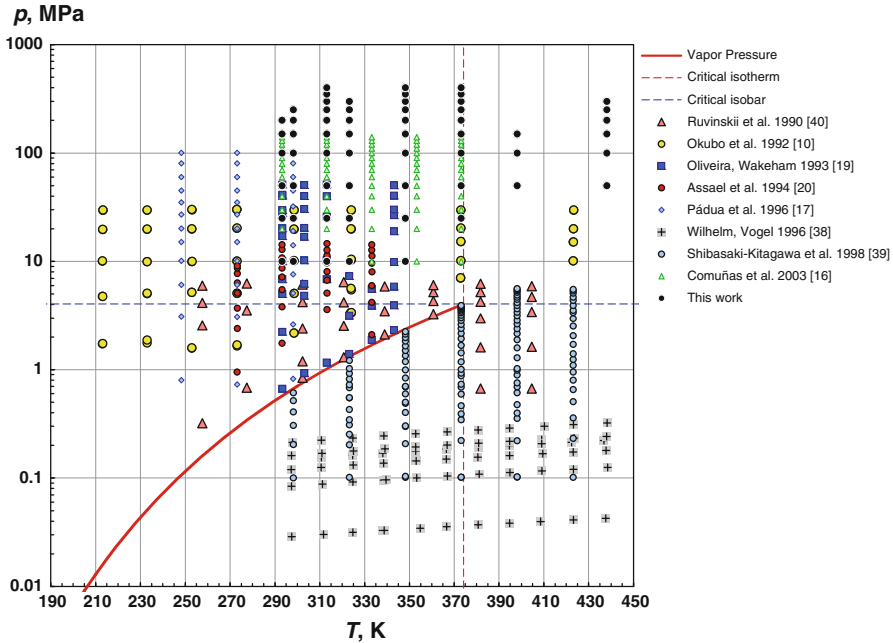


Fig. 9 Pressure and temperature range of the present measurements and of selected literature data for the viscosity of R134a

and a reported uncertainty of 0.5 % range between -3.4% and -8.2% below the scaling function. The third set of results measured with a vibrating-wire viscometer of a reported uncertainty of 0.6 % by Oliveira and Wakeham [19] deviates from the scaling function in a similar pattern as the two aforementioned ones but with wider scatter. Some of these deviations arise because the scaling function Eq. 5 is not adequate at low densities.

The results of Okubo et al. [10], measured with a pressurized capillary viscometer of a reported uncertainty of 1.3 % over a wide temperature range from 213 K to 423 K, deviate from the scaling function between -19% and 7 %. These wide-ranging deviations arise because the scaling function Eq. 5 captures the viscosity-temperature dependence only partially and because it is not adequate at low pressures. Other measurement results that were obtained with capillary viscometers, such as those by Ruvinskii et al. [40] and by Laesecke et al. [8] show deviations from the scaling function, Eq. 5, that are consistent with those of the data by Okubo et al. They were not included in Fig. 10 for clarity.

A systematic deviation cluster is observed in Fig. 10 for the results of Comuñas et al. [16]. Their uncertainty was reported as 2 % for the (293.15, 313.15, and 333.15) K isotherms, 3 % for the 353.15 K isotherm, and 4 % for the 373.15 K isotherm. The deviations range above those of the other literature data and largely above the scaling function. Their internal consistency changes above 30 MPa, where a noticeable temperature dependence becomes discernible per isotherm. The maximum deviation is 11 % at 373.15 K and 80 MPa, respectively. Some of the deviations of the present

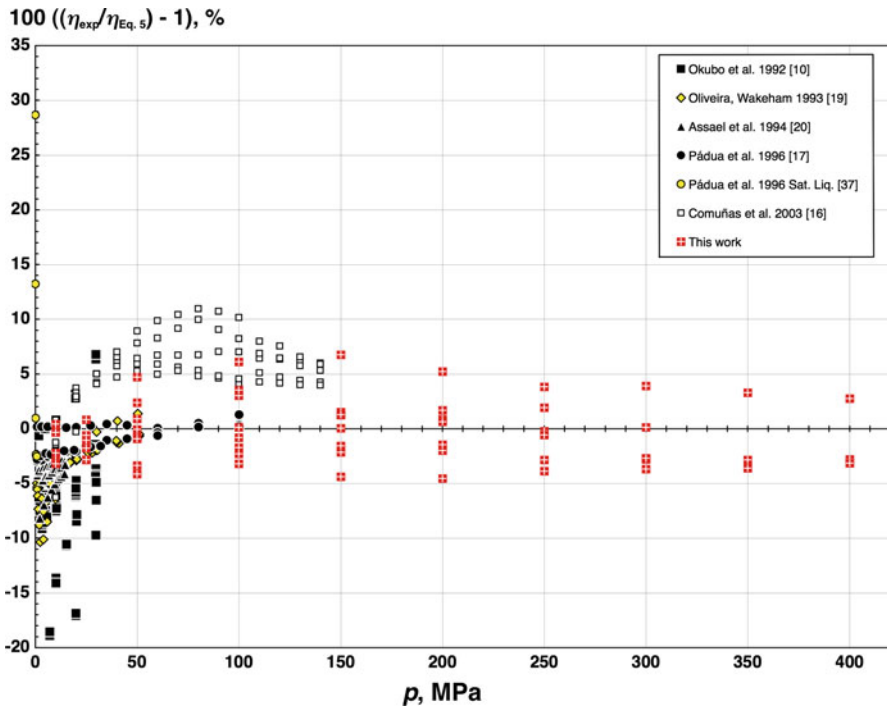


Fig. 10 Percent deviations of the present measurement results and of literature data for the viscosity of R134a from the scaling function, Eq. 5

results coincide with those of the results of Comuñas et al. However, the scatter of the present results is less systematic than that of the results of Comuñas et al.

6 Concluding Remarks

The viscosity of R134a was measured with a guided falling-cylinder viscometer at temperatures from 293.15 K to 438.15 K with pressures from 10 MPa to 400 MPa. The maximum pressure corresponds to 99 times the critical pressure of this compound. Only a few fluids have been characterized by viscometry to that extent.

The most recent correlations for the viscosity of R134a by Huber et al. [15] and by Scalabrin et al. [18] cannot be used for extrapolations in that data range. Figure 11 shows that the correlation of Huber et al. overestimates the viscosity of R134a by up to 5921% when extrapolated to the maximum pressure of the new measurements reported here. The pattern of the deviations is indicative for the divergence of the free-volume term in that correlation. A wider ranging correlation can now be developed based on the new high-pressure data measured in this study. An expanded-range correlation is of particular importance for the viscosity of R134a, because the compound is used as a reference fluid in the framework of extended corresponding states [15] to predict viscosities of compounds with similar molecular structures. It will also

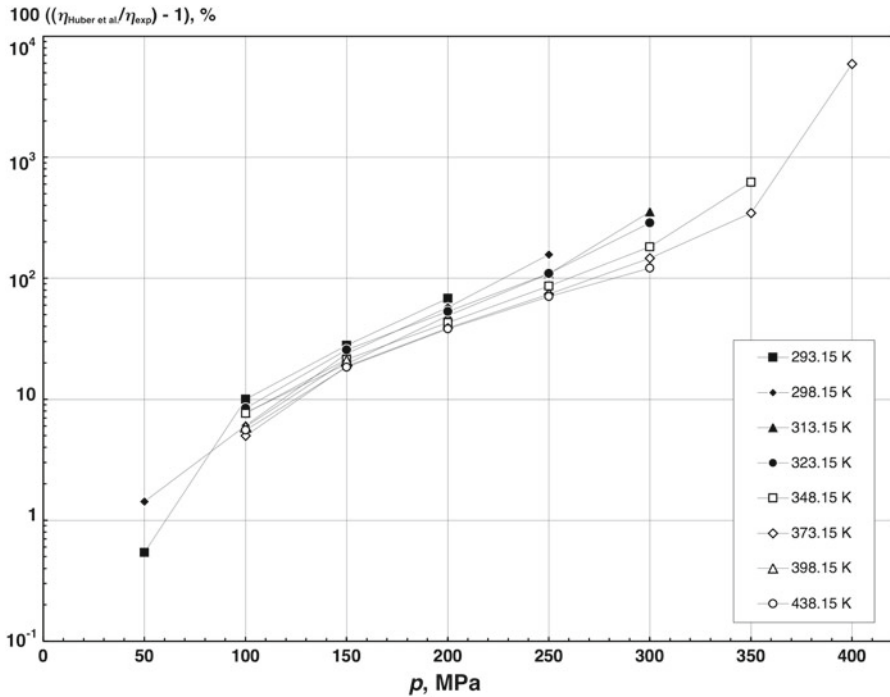


Fig. 11 Percent deviations of viscosity values calculated with the extrapolated correlation of Huber et al. [15] from the present measurement results

contribute more accuracy to the tribological engineering of compressors with refrigerant working fluids.

The present measurement results were correlated in terms of the Ashurst-Hoover scaling factor that combines temperature and density as independent variables. The viscosity could be expressed as an exponential power law in terms of the Ashurst-Hoover factor with four adjustable parameters. This simple expression exhibits remarkable capabilities to represent data in the compressed liquid region and to be extrapolated with meaningful results. For instance, adjusting the parameters γ , η_0 , A , and q in Eqs. 2 and 5 to the data of Pádua et al. [17] yields extrapolations to the present measurement results with deviations between -4.4% and 10% . This is substantially closer than extrapolating the correlation of Huber et al. [15]. Another advantage of power-law terms based on the Ashurst-Hoover scaling factor is that they are related to the repulsive part of the intermolecular force field.

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