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This is the author's submitted version of the contribution published as:

Original
Experimental liquid densities of cis -1,3,3,3-tetrafluoroprop-1-ene (R1234ze(Z)) and trans -1-chloro-3,3,3-trifluoropropene (R1233zd(E)) / Romeo, R.; GIULIANO ALBO, PAOLO ALBERTO; Lago, Simona; Brown, J. S.. - In: INTERNATIONAL JOURNAL OF REFRIGERATION. - ISSN 0140-7007. - 79:(2017), pp. 176-182. [10.1016/j.ijrefrig.2017.04.003]

Availability:
This version is available at: 11696/56345 since: 2021-08-24T16:00:02Z

Publisher:
Elsevier

Published
DOI:10.1016/j.ijrefrig.2017.04.003

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24 April 2024

Experimental liquid densities of *cis*-1,3,3,3-tetrafluoroprop-1-ene (R1234ze(Z)) and *trans*-1-chloro-3,3,3-trifluoropropene (R1233zd(E))

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Abstract

In this work, liquid phase densities of two fourth generation refrigerants, *cis*-1,3,3,3-tetrafluoroprop-1-ene R1234ze(Z) and *trans*-1-chloro-3,3,3-trifluoropropene R1233zd(E), are measured. The densities have been measured using a vibrating tube densimeter over the temperature range from (273.15 to 333.15) K for pressures up to 30 MPa. For both fluids, the expanded uncertainty at a confidence level of 95% in the density measurements is estimated to be 0.07% over the entire T-p range measured.

Keywords: density, R1234ze(Z), R1233zd(E), high pressure

1. Introduction

In recent years, the interest in new working fluids, e.g. refrigerants, is growing due to regulations being adopted and implemented to tackle global warming as established by the Kyoto Protocol (1997). This fourth generation of refrigerants (Calm, 2008), in addition to needing to possess attributes such as low toxicity, low flammability, short atmospheric lifetime, and near-zero ozone depleting potential (ODP), must also possess low or ultra-low global warming potential (GWP) UNEP (2014).

The refrigerant *cis*-1,3,3,3-tetrafluoroprop-1-ene, i.e. HFO-1234ze(Z), is a hydrofluoroolefin which has zero ODP, an atmospheric lifetime of 10 days and a 100-year time horizon GWP lower than 6 (Akasaka et al., 2014). The refrigerant *trans*-1-chloro-3,3,3-trifluoropropene, i.e. HCFO-1233zd(E), is a hydrochlorofluoroolefin which has a near-zero ODP, an atmospheric lifetime of 26 days, and a GWP lower than 7 (Orkin et al., 2014). Thus, these two fluids hold promise as two possible candidates as substitutes for previous generation refrigerants. Despite this fact, the open literature contains few experimental data of the thermodynamic properties for these refrigerants. Regarding density, Kayukawa et al. (2012) measured compressed liquid and saturated liquid density of R1234ze(Z) in the temperature range from (310 to 420) K for pressures up to

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5 MPa. Higashi et al. (2013) and Tanaka et al. (2013) performed the same type of measurements from (360 to 432) K up to 6 MPa and from (310 to 410) K up to 5 MPa, respectively. The compressed liquid density of R1234ze(Z) was also measured by Fedele et al. (2014) from (283 to 363) K for a much wider pressure range than previously considered, that is, up to 35 MPa. Regarding R1233zd(E), currently there are only two published papers presenting experimental density data: measurements carried out by Mondéjar et al. (2015) over the temperature range from (215 to 444) K for pressures up to 24.1 MPa and by Tanaka (2016) from (328 to 443) K for pressures up to 10 MPa.

Therefore, in this paper, we wish to add to the publicly available literature a number of experimental compressed liquid density measurements for R1234ze(Z) and R1233zd(E), and in doing so extend the temperature and pressure ranges beyond those previously considered. The measurements were performed using a commercial vibrating tube densimeter over the temperature range (273.15 to 333.15) K for pressures up to 30 MPa.

2. Experimental section

Vibrating-tube densimeters are widely used for accurate measurements of fluids both in the gaseous and liquid phases, finding applications both in research and in industry. Some of the most attractive characteristics of these densimeters are their high precision, operational simplicity and the small amount of sample volume required to make the measurements. The working principle of vibrating-tube densimeters is based on measuring the mechanical resonant frequency of a U-tube, filled with the sample fluid, when it is excited by a piezoelectric external transducer coupled with the measurement cell. The oscillation periods, corresponding to the value of a resonant frequency, are directly correlated to the value of the sample density, which depends mainly on the working temperature and pressure. Therefore, the vibrating tube densimeter consists of a glass (to measure at atmospheric pressure) or metallic (to measure at high pressure) U-shaped capillary tube, with a volume of a few cubic centimeters, isolated in a thermostatic test cell. The tube is filled with the sample of interest and vibrates perpendicular to its plane by means of a piezoelectric transducer. The period, τ, of the harmonic oscillation of the tube can be directly related to the density, ρ, of the fluid contained in the tube by:

$$\rho(T,p) = A(T,p) \cdot \tau^2(T,p) - B(T,p) \quad , \tag{1}$$

where A and B, both of which are dependent on temperature and pressure, are characteristic parameters of the instrument, defined as

$$A = \frac{K(T,p)}{4\pi^2 V(T,p)} \quad ; \quad B = \frac{M_0}{V(T,p)} \quad , \tag{2}$$

where K is the tube stiffness, V is the tube inner volume and M_0 is the evacuated tube mass.

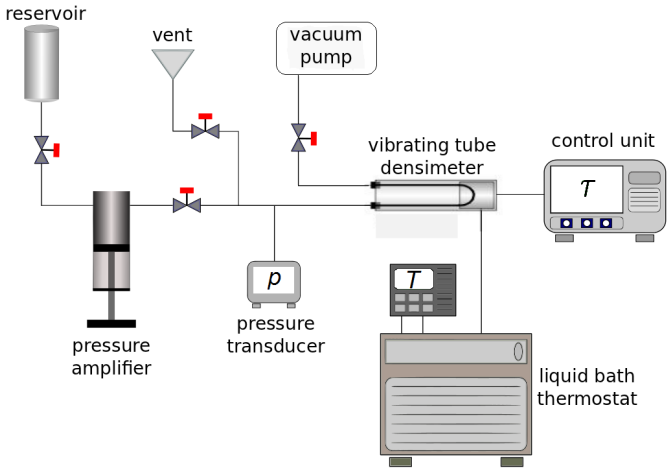

Figure 1: Schematic representation of the experimental apparatus used in this work.

The experimental apparatus for density measurements is schematically shown in Fig. 1. It mainly consists of an Anton Paar DMA 512P vibrating tube densimeter connected to an Anton Paar DMA 5000 densimeter, used as a counter unit. The temperature of the measurement cell, which contains the vibrating tube, is thermostatically controlled by a liquid bath. The sample temperature is measured using a PT100 platinum resistance thermometer coupled with a thermometer readout resulting in an expanded uncertainty of 0.01 K. Details of the experimental apparatus are provided in Giuliano Albo et al. (2013).

2.1. Calibration procedure

In order to characterize and determine the instrument parameters defined in Eq. 2, the vibrating periods of two reference fluids of known density need to be measured. In order to simplify the calibration procedure, the period is usually measured in an evacuated tube and one charged with water. Following this procedure, the unknown density can be obtained through the relation

$$\rho(T,p) = \rho_{\mathrm{w}}(T,p)\frac{\tau^2(T,p) - \tau_0^2(T)}{\tau_{\mathrm{w}}^2(T,p) - \tau_0^2(T)} \quad , \tag{3}$$

where τ, τ_{w}, τ_0 are the measured periods related to the oscillation of the tube filled with the sample, i.e., evacuated and charged with water. For the present work, the calibration of the vibrating tube densimeter was performed using water as the reference fluid while calibrating in a vacuum. The oscillation period of pure water was measured in the temperature range from (273.15 to 333.15) K, along 6 isotherms, and for pressure from (1 to 30) MPa, i.e., the same thermodynamic states over which the refrigerants are measured. The water densities used in the formula are the values provided by the reference equation

of state of Wagner and Pruss (2002), which has a maximum uncertainty of 0.003% over the T-p range considered.

2.2. Uncertainty

In order to estimate the expanded uncertainty of density, it was considered as a function of pure water density ρ_{w}, vibrating periods τ, τ_{w}, τ_0, temperature T and pressure p:

$$\rho = \rho(\rho_{\mathrm{w}}, \tau, \tau_{\mathrm{w}}, \tau_0, T, p) \tag{4}$$

Consequently, propagation of uncertainty as shown below was carried out in order to estimate the relative uncertainty of the water density

$$\frac{u(\rho)}{\rho} = \left[\left(\frac{\partial \rho}{\partial \rho_{\mathrm{w}}} \right)^2 u^2(\rho_{\mathrm{w}}) + \left(\frac{\partial \rho}{\partial \tau} \right)^2 u^2(\tau) + \left(\frac{\partial \rho}{\partial \tau_{\mathrm{w}}} \right)^2 u^2(\tau_{\mathrm{w}}) + \left(\frac{\partial \rho}{\partial \tau_0} \right)^2 u^2(\tau_0) + \left(\frac{\partial \rho}{\partial T} \right)^2 u^2(T) + \left(\frac{\partial \rho}{\partial p} \right)^2 u^2(p) \right]^{0.5} . \tag{5}$$

The uncertainty in the reference water density is fromWagner and Pruss (2002) and is provided above. For the vibrating period, the uncertainty is 0.1 μs, corresponding to the repeatability of ten readings at each measuring point. The uncertainty of the calibrated PT100 resistance thermometer is 0.03 K. The pressure transducer uncertainty is 0.03 MPa. The relative uncertainty in the density measurements of density is calculated using Eq. 5 with a coverage factor of 2. The resulting uncertainty is 0.07% at the confidence level of 95%. Table 1 provides the sources and associated uncertainties contributing to the density uncertainty. Table 1 demonstrates that the major contributor to the density uncertainty resuls from uncertainties in the vibrating period measurements.

Table 1: Density uncertainty budget.

Uncertainty source	Relative magnitude %
water density	0.004
oscillation period	0.070
temperature	0.001
pressure	0.001
Estimated overall uncertainty (k=2)	**0.07**

3. Density results

The experimental densities presented in this paper were calculated using Eq. 3. However, it should be pointed out that there are multiple ways that one could analyze the measurements taken with a vibrating tube densimeter. Particularly, in several papers such as ones by Fedele et al. (2014), Bouchot

and Richon (2001), Outcalt and McLinden (2007) or Comuñas et al. (2008), the authors use different fitting functions to correlate the experimental values or to calculate the densities. For example, in Comuñas et al. (2008) the function used to calculate the densities comes from considering that both instrument paramenters A and B are pressure dependent; whereas the method presented herein considers the parameter B to be pressure independent. Regardless, the differences between the two approaches have been confirmed to be negligible by the present authors.

3.1. R1234ze(Z) density results

R1234ze(Z) in the compressed liquid state was measured over the pressure range from (1 to 30) MPa, along five isotherms: (273.15, 283.15, 293.15, 313.15, 333.15) K. Since the densimeter calibration was carried out using water as the reference fluid, the 273.15 K isotherm consists of only the data at 25 MPa and 30 MPa. The density values at each measured temperature and pressure are reported in Table 2. Figure 2 shows a plot of the experimental densities calculated by Eq. 3 as a function of pressure along the five isotherms.

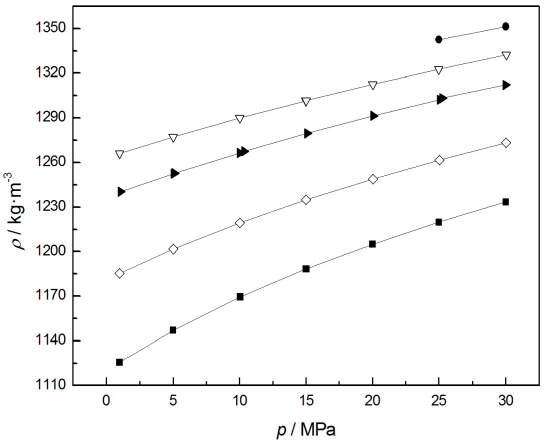

Figure 2: R1234ze(Z) compressed liquid densities as a function of pressure: (●), $T = 273.15$ K; (▽), $T = 283.15$ K; (▶), $T = 293.15$ K; (◇), $T = 313.15$ K; (■), $T = 333.15$ K.

The experimental results were compared with the fundamental equation of state for R1234ze(Z) developed by Akasaka et al. (2014), even though it was developed without access to experimental liquid density data.

Fig. 3 reports the deviations of the experimental values from the equation of state (zero line) as a function of pressure. Although the declared validity of the Akasaka equation is for pressures up to 6 MPa, Fig. 3 shows deviations over the entire pressure range considered herein. Considering that the equation has

Table 2: Experimental R1234ze(Z) density ρ at temperature T and pressure p.

T/K	p/MPa	ρ/kg·m^{-3}
273.154	25.00	1342.58
273.145	30.01	1351.38
283.148	1.00	1266.05
283.151	5.01	1277.22
283.149	10.01	1290.00
283.153	15.00	1301.59
283.153	15.01	1301.63
283.148	20.02	1312.54
283.151	24.99	1322.61
283.153	30.05	1332.32
293.146	1.08	1240.34
293.154	5.05	1252.39
293.143	5.11	1252.83
293.153	10.03	1266.48
293.147	10.35	1267.52
293.148	15.09	1279.66
293.147	20.07	1291.49
293.153	25.08	1302.24
293.150	25.26	1303.34
293.150	30.00	1312.22
313.156	1.00	1185.36
313.154	1.02	1185.46
313.152	5.01	1201.61
313.152	10.03	1219.29
313.150	15.01	1234.80
313.150	20.04	1248.91
313.151	25.05	1261.67
313.153	30.03	1273.33
333.148	1.00	1125.59
333.156	5.00	1146.91
333.150	10.06	1169.46
333.152	15.00	1188.23
333.152	15.03	1188.32
333.151	20.00	1204.91
333.152	25.00	1219.84
333.151	30.00	1233.41

a stated uncertainty of 0.2% for liquid density, most of the measurements are in agreement with Akasaka's equation.

Furthermore, the densities presented herein were also compared with the measurements carried out by Fedele et al. (2014), also using a vibrating tube

densimeter, for temperatures from (283 to 363) K for pressures up to 35 MPa. The deviations of our results from Fedele et al. densities are shown in Fig. 4. The deviations systematically increase as the pressure increases, but considering the uncertainty declared by Fedele et al. (2014) (maximum uncertainty of 0.07%) all the experimental data are in agreement.

From the period measurements, the densities were also calculated following the method used in Comuñas et al. (2008), in order to compare the two different methods. Figure 5 presents the deviations of the densities using the two methods: most of the deviations are lower than the uncertainty, demonstrating that there is no major difference between the two methods at low pressures, with just three data points at the higher pressures (25 MPa and 30 MPa) deviating up to about 0.1%.

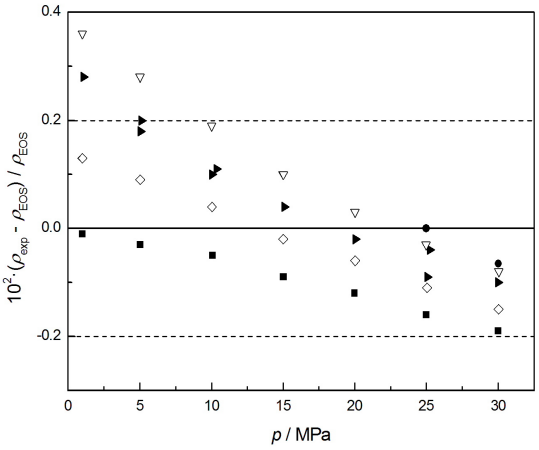

Figure 3: Deviations of R1234ze(Z) experimental densities from the fundamental equation of state of Akasaka et al. (2014) as a function of pressure: (●), $T = 273.15$ K; (▽), $T = 283.15$ K; (►), $T = 293.15$ K; (◇), $T = 313.15$ K; (■), $T = 333.15$ K; the dashed lines represent the stated uncertainty of Akasaka et al. liquid density.

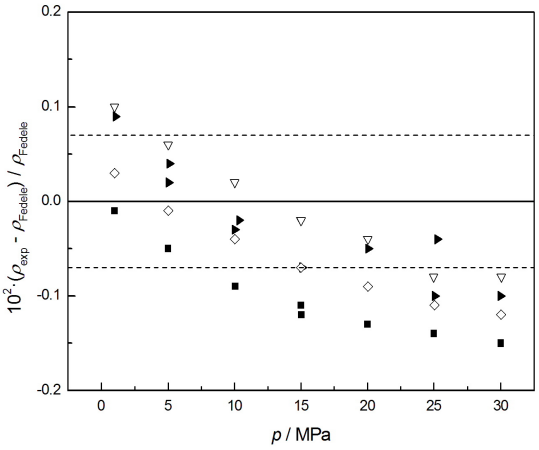

Figure 4: Deviations of R1234ze(Z) experimental densities from the measurements of Fedele et al. (2014) as a function of pressure: (▽), $T = 283.15$ K; (▶), $T = 293.15$ K; (◇), $T = 313.15$ K; (■), $T = 333.15$ K; the dashed lines represent the maximum uncertainty of Fedele et al. densities.

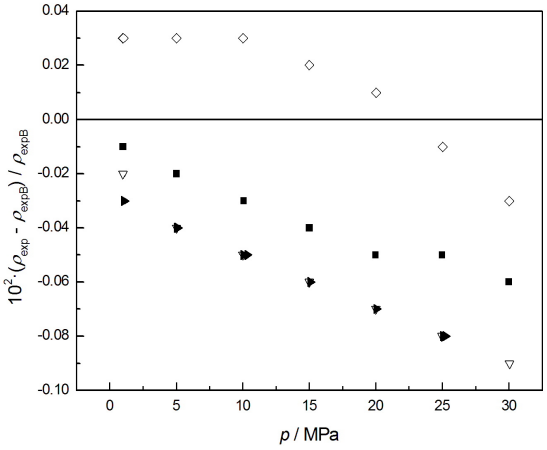

Figure 5: Deviations of R1234ze(Z) experimental densities from the experimental values calculated by the B pressure dependent method as a function of pressure: (▽), $T = 283.15$ K; (▶), $T = 293.15$ K; (◇), $T = 313.15$ K; (■), $T = 333.15$ K.

3.2. R1233zd(E) density results

The compressed liquid density of R1233zd(E) was measured along five isotherms (274.15, 283.15, 293.15, 313.15, 333.15) K for pressures from (1 to 25) MPa. In Table 3, the experimental density values at each measured temperature and pressure are reported, while Fig. 6 shows R1233zd(E) densities as a function of pressure along the five isotherms. The experimental results were compared to the fundamental equation of state developed by Mondéjar et al. (2015). Fig. 7 provides the deviations of the experimental values from the equation of state (zero line) as a function of pressure. Figure 7 shows that all the deviations are within ±0.06%, demonstrating that all the measurements are in good agreement with the existing equation.

The density of R1233zd(E) was also calculated by using the B pressure dependent method, and the results are compared with the densities obtained by Eq. 3. The deviations between the two methods are shown in Fig. 8, with all the deviations being lower than 0.08%. Similar to the case of R1234ze(Z), the larger deviations correspond to the higher pressures.

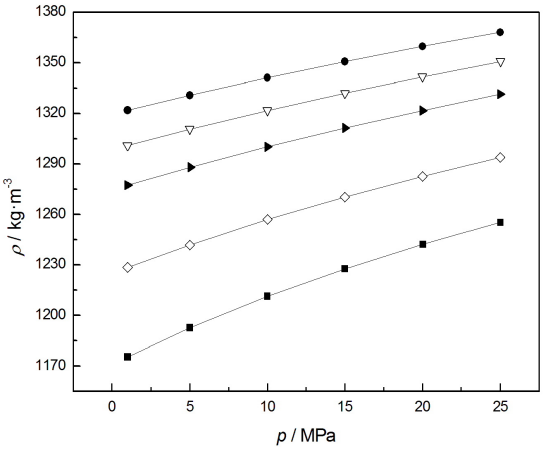

Figure 6: R1233zd(E) compressed liquid densities as a function of pressure: (●), $T = 274.15$ K; (▽), $T = 283.15$ K; (►), $T = 293.15$ K; (◇), $T = 313.15$ K; (■), $T = 333.15$ K.

Table 3: Experimental R1233zd(E) density ρ at temperature T and pressure p.

T/K	p/MPa	ρ/kg·m^{-3}
274.150	1.00	1321.95
274.147	5.00	1330.84
274.151	10.00	1341.16
274.150	15.00	1350.75
274.149	20.01	1359.73
274.149	25.00	1368.12
283.154	1.00	1301.12
283.148	5.00	1310.73
283.150	10.00	1321.78
283.147	15.01	1332.07
283.148	20.00	1341.64
283.153	25.01	1350.73
293.152	1.00	1277.44
293.151	5.04	1288.16
293.149	10.02	1300.25
293.151	15.01	1311.40
293.152	20.01	1321.80
293.151	25.00	1331.52
313.152	1.00	1228.52
313.152	4.99	1241.96
313.151	10.00	1257.00
313.150	15.00	1270.49
313.152	20.01	1282.69
313.147	25.00	1293.96
333.149	1.00	1175.46
333.151	5.00	1192.70
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333.152	15.00	1227.66
333.146	20.04	1242.27
333.147	25.01	1255.26

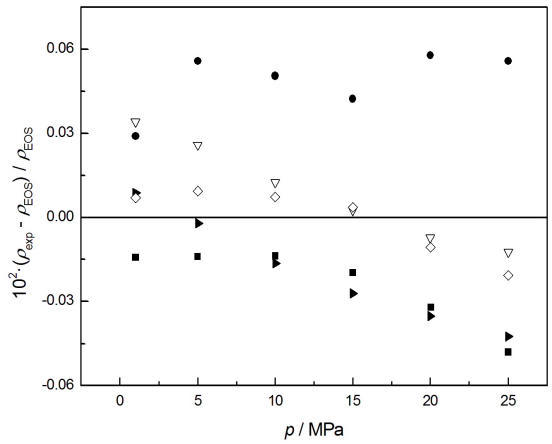

Figure 7: Deviations of R1233zd(E) experimental densities from the fundamental equation of state of Mondéjar et al. (2015) as a function of pressure: (●), $T = 273.15$ K; (▽), $T = 283.15$ K; (▶), $T = 293.15$ K; (◇), $T = 313.15$ K; (■), $T = 333.15$ K.

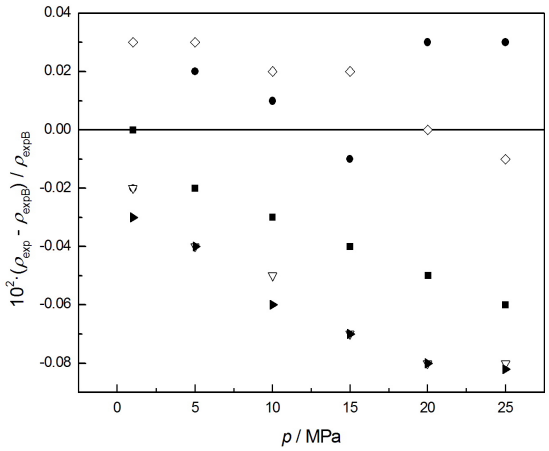

Figure 8: Deviations of R1233zd(E) experimental densities from the experimental values calculated by the B pressure dependent method as a function of pressure: (●), $T = 273.15$ K; (▽), $T = 283.15$ K; (▶), $T = 293.15$ K; (◇), $T = 313.15$ K; (■), $T = 333.15$ K.

4. Conclusion

Since there is on-going and growing interest in environmentally-friendly, alternative refrigerants possessing low and ultra-low GWP values and the need for additional measured data of these fluids, this paper places in the publicly available literature density measurements of R1234ze(Z) and R1233zd(E).

The density measurements were taken using a vibrating tube densimeter (Anton Paar 512P) over the temperature range from (273.15 to 333.15) K and for pressures from (1 to 30) MPa with an expanded uncertainty of 0.07% at the 95% confidence level.

The measured densities of R1234ze(Z) were compared with the fundamental Helmholtz equation of state of Akasaka et al. (2014). Although the equation is valid for pressures only up to 6 MPa, it is in good agreement with the experimental data reported herein. In addition, the measured values were also compared with the measured densities of Fedele et al. (2014), with both datasets demonstrating good agreement over the entire T-p range. The experimental densities of R1233zd(E) were also compared with the dedicated fundamental Helmholtz equation of state of Mondéjar et al. (2015), demonstrating good agreement with the experimental data reported herein.

In this work the density results were calculated using two different density functions: the first considered one of the instrument's fitting parameters to be pressure dependent and the second method considered it to be pressure independent. Since the measurements were carried out at pressures up to 30 MPa, the two methods resulted in differences that were negligible.

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