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High Pressure Density and Speed of Sound of Hydrofluoroether Fluid
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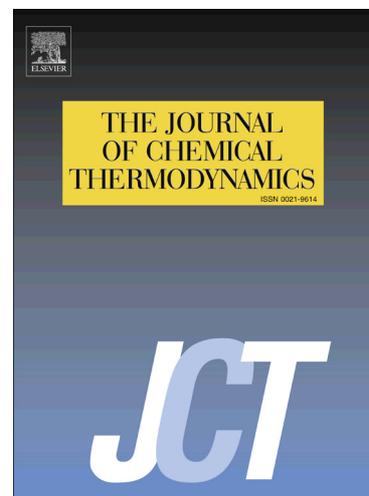
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High Pressure Density and Speed of Sound of Hydrofluoroether Fluid 1,1,1,2,2,3,4,5,5,5-decafluoro-3-methoxy-4-(trifluoromethyl)-pentane (HFE-7300).

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Abstract

High pressure density measurements were carried out for the hydrofluoroether fluid HFE-7300. A total of 159 points have been measured in the pressure range from 0.1 to 140 MPa and along seven isotherms within the temperature interval (293.15 - 393.15) K. To perform these measurements, an Anton Paar vibrating tube densitometer was used. The experimental high pressure density data were correlated to a Tait-like equation and compared with the available literature. By deriving the Tait-like equation, the isothermal compressibility and isothermal compressibility were also determined in the same P and T ranges. The speed of sound measurements were performed along six isotherms from 293.15 to 333.15 K at 0.1 MPa. The isentropic compressibilities were also calculated from speed of sound and density data by means of the Laplace equation.

Keywords

Hydrofluoroethers, Density, Isobaric Expansion, Isothermal Compressibility, Speed of Sound.

1. Introduction

Industry needs a broad range of fluids to meet their requirements on heat transfer, cleaning applications, lubricant deposition and electronics applications such as cooling, front end semiconductor wafer processing and back end integrated circuit packaging [1 - 3].

Over time, a wide variety of compounds (mineral oils, silicone oils, perfluorocarbons (PFC), perfluoropolyethers (PFPE), etc.) have been used for these purposes due to their desirable physicochemical properties, but often without taking into account their environmental impact.

PFC liquids are used because they are chemically inert and non-flammable, they have high dielectric strength and electrical resistivity, and they evaporate cleanly [4]. Amongst the drawbacks, they exhibit long atmospheric lifetimes and high global warming potentials (GWP), which are non-desirable properties for the environment, even they are non-ozone depleting agents. Something similar occurs for PFPE: their physicochemical properties are of interest for the aforementioned purposes, but their high GWP and large atmospheric lifetimes require search for other environmentally friendly fluids.

Segregated hydrofluoroethers (HFEs) are a class of fluids synthesized since the '90s. In its structure a perfluorocarbon segment is separated from a hydrocarbon segment by an ether oxygen, which brings environmentally desirable properties such as short atmospheric lifetimes, in the order of 3 years or less. Also, these kind of compounds have zero or near-zero ozone depletion potentials (ODP) and low global warming potentials. The variety of HFEs synthesized offer a wide useful temperature ranges, a relatively high thermal capacity, low viscosity and high liquid density, being also non-flammable, inert to common metals and polymers, and exhibiting very low overall toxicity [5].

1,1,1,2,2,3,4,5,5-decafluoro-3-methoxy-4-(trifluoromethyl)-pentane, also known as HFE-7300, is a segregated hydrofluoroether which can be used in heat transfer applications, cleaning applications, and in lubricant deposition. The properties knowledge about this fluid is scarce. Some papers report its environmental properties: reference [6] reports the low contribution of HFE-7300 to the atmospheric warming even though this compound is highly fluorinated. This reference also states that HFE-7300 is effective at mitigating the aggressiveness and the flammability of solvents, so this fluid can be used as pure compound or in mixture with other fluids. Some patents [7] propose several mixtures of HFE-7300 with other flammable compounds to be used as electronics cleaning agents, lubricants, and heat transfer fluids.

This work provides experimental density data for pure HFE-7300 in the pressure range (0.1 – 140) MPa and in the temperature interval (293.15 – 393.15) K. Correlation of data was performed by using a Tait-like equation, and also the derived properties, that is, the isothermal compressibility, κ_T , and the isobaric expansion, α_P were calculated. A comparison of density data was done with the only reference found at atmospheric pressure, being no high pressure density data available in the literature. Speed of sound was measured at 0.1 MPa and at temperatures (293.15 – 333.15) K. Isentropic compressibility was determined in the same temperature range.

2. Experimental

2.1 Materials

The hydrofluoroether fluid 1,1,1,2,2,3,4,5,5-decafluoro-3-methoxy-4-(trifluoromethyl)-pentane, known as HFE-7300, ($C_7H_3F_{13}O$, molar mass 350 g·mol⁻¹, CAS number 132182-92-4) was supplied by the 3M Company (Novec Engineered Fluids) with a mass purity greater than 0.995. No further purification method was carried out before using, only careful degassing with an ultrasound bath to prevent bubbles formation.

2.2. Apparatus and procedure

To carry out the high pressure density measurements with HFE-7300, a vibrating tube densitometer Anton Paar, model DMA HPM, was used. With this apparatus, the measurements were performed from 0.1 MPa up to 140 MPa, with 5 MPa intervals from 0.1 MPa to 65 MPa, and at every 10 MPa from 70 MPa to 140 MPa for the pressure P . For the temperature T , a thermostatic bath connected with the densitometer allows to set a wide range of temperatures,

being the measurements performed along seven isotherms (293.15, 298.15, 313.15, 333.15, 353.15, 373.15 and 393.15) K. The experimental setup was described previously [8]. The calibration of the densitometer was performed according to the procedure described by Comuñas *et al.* [9] which is a modification of the procedure previously proposed by Lagourette *et al.* [10]. Two reference fluids were used in order to perform the calibrations, vacuum and water. These fluids were selected because there is vast knowledge about their properties. For water, although there are lots of data concerning density values, we took those from the equation of state (EoS) reported by Wagner and Pruss [11].

The sample was prepared by filling a stoppered bottle of 21 cm³ and degassing it with an ultrasound bath PSelecta, model Ultrasons H, to prevent bubbles formation and consequently an air intake in the densitometer. When vacuum is done inside the densitometer, the sample enters the system by suction. After closing the fluid inlet valve, and when the sample reaches the thermal and mechanical equilibrium, the density measurement starts. The DMA HPM measuring cell is connected to the Anton Paar mPDS 2000V3 evaluation unit, which evaluates the oscillation period from the measuring cell filled with the sample. Depending on the mass of the sample, the temperature and the pressure, the oscillation period of the cell changes. Then, it is possible to determine the density values from the given values of period. In this way, a total of 159 points were measured within the pressure and temperature ranges established.

Concerning the uncertainties, the Pt 100 probe that is directly inserted into the densitometer leads to an expanded uncertainty in temperature of 0.03 K. For the pressure, the expanded uncertainty is 0.04 MPa (pressure transducer WIKA CPH 6000). Then, the estimated expanded uncertainty ($k = 2$) in density, calculated following the EA-4/02 document [12], taking into account the accuracy of the temperature, the pressure, the period of oscillation measurement for water, vacuum, the studied system, and the water density accuracy, is estimated to be $0.7 \cdot 10^{-3} \text{ g} \cdot \text{cm}^{-3}$ (*i.e.*, around 0.07 % for density close to water density).

The speed of sound, c , in pure HFE-7300 was measured by using an Anton Paar DSA 5000 vibrating tube densitometer and sound analyzer automatically thermostatted within ± 0.01 K. This device uses a propagation time technique [13 - 15] to determine the speed of sound of the sample. The apparatus has two transducers in which one acts as an emitter, and the other as receiver, working in a frequency of approximately 3 MHz. The measurements were performed at 0.1 MPa and at temperatures: 293.15, 298.15, 303.15, 313.15, 323.15 and 333.15 K. The calibration of this apparatus, performed once a week and every time a new temperature was set, was made with ambient air and Millipore quality water following the manufacturer's instructions. The results of the calibrations were compared with those of references [11] for water, and [16] for air. Prior to make any measurement, the samples were degassed for at least 15 minutes in an ultrasonic bath PSelecta model Ultrasons H. The standard uncertainty for the ambient pressure (0.1 MPa), measured by using a Lambrecht model 604 barometer, is determined to be $U(P_{0.1}) = 10^{-4}$ MPa. The accuracy for the speed of sound measurements is $0.5 \text{ m} \cdot \text{s}^{-1}$, being the expanded uncertainty $1 \text{ m} \cdot \text{s}^{-1}$. In order to calculate the isentropic

compressibility, κ_S , densities were also measured with the same apparatus due to the high pressure density measurements do not include the points at atmospheric pressure and at temperatures 303.15 and 323.15 K. The accuracy for the density is $5 \cdot 10^{-6} \text{ g}\cdot\text{cm}^{-3}$ while the expanded uncertainty in density is $9 \cdot 10^{-4} \text{ g}\cdot\text{cm}^{-3}$.

3. Results and Discussion

3.1. Experimental density data

High pressure density measurements of pure HFE-7300 fluid were performed along seven isotherms ranging from 293.15 K to 393.15 K and along 23 isobars from 0.1 MPa up to 140 MPa. Due to the boiling point of HFE-7300 at 0.1 MPa is 371.15 K [5], no measurements were performed at 373.15 K and at 393.15 K at this pressure to avoid gaseous state and to ensure all the measurements were performed in liquid state. Table 1 shows the density values measured experimentally with the high pressure densitometer.

3.2. Tait representation

A Tait-like equation was used to correlate the experimental high pressure density data in order to be able to interpolate values at different pressures or temperatures within our pressure and temperature ranges. The Tait-like equation proposed was used in our previous works [17 - 19].

$$\rho(T,p) = \frac{\rho_0(T)}{1 - C \ln\left(\frac{B(T) + p}{B(T) + 0.1 \text{ MPa}}\right)} \quad (1)$$

where

$$\rho_0(T) = A_0 + A_1T + A_2T^2 + A_3T^3 \quad (2)$$

$$B(T) = B_0 + B_1T + B_2T^2 \quad (3)$$

The A_i , B_i and C parameters values were determined by correlating simultaneously all the experimental densities values versus pressure and temperature.

To compare the experimental density values with those obtained with the correlation considered in this work, we have used the Absolute Average Deviation (AAD%), the Maximum Deviation (MD%), and the Average Deviation (AD%), which are defined as follows:

$$\text{AAD} = \frac{100}{N} \sum_{i=1}^N \left| \frac{\rho_i^{\text{exp}} - \rho_i^{\text{calc}}}{\rho_i^{\text{exp}}} \right| \quad (4)$$

$$\text{MD} = \text{Max} \left(100 \left| \frac{\rho_i^{\text{exp}} - \rho_i^{\text{calc}}}{\rho_i^{\text{exp}}} \right| \right) \quad (5)$$

$$AD = \frac{100}{N} \sum_{i=1}^N \frac{\rho_i^{\text{exp}} - \rho_i^{\text{calc}}}{\rho_i^{\text{exp}}} \quad (6)$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^N (\rho_i^{\text{exp}} - \rho_i^{\text{calc}})^2}{N-m}} \quad (7)$$

$$\text{RMSD} = \sqrt{\frac{\sum_{i=1}^N (\rho_i^{\text{exp}} - \rho_i^{\text{calc}})^2}{N}} \quad (8)$$

where N is the number of experimental data ($N = 159$) and m is the number of parameters ($m = 8$).

The eight A_i , B_i and C calculated parameters of the Tait-like equation and the statistical values obtained with this correlation are given in Table 2 for HFE-7300.

In this work, it has to be noted that all the fitting deviations (the AAD%, MD%, AD%, the standard deviation σ and the RMSD) are lower than the experimental uncertainty in density ($\pm 0.07\%$). This fact can be also verified in Figure 1 (a) where the average deviations are plotted versus the pressure considering all the temperatures measured, and in Figure 1 (b) where the deviations are showed against the temperature for several pressure values.

Figure 2 (a) shows a comparison between the experimental density values ρ , and those obtained with the correlation equations (1 – 3) versus the pressure, for the seven isotherms measured. It can be seen the non-linear behaviour of the density versus the pressure, particularly at high temperatures. The shape of this curves is compatible with the logarithmic relationship used in the Tait-like equation used to model the influence of pressure on density.

It can be stated also that for all the temperatures the values of density increase when increasing the pressure. In the same manner, the lower the temperature, the higher the values of density, being the maximum at 293.15 K and at 140 MPa with a value in density of $1.8788 \text{ g}\cdot\text{cm}^{-3}$.

Figure 2 (b) presents the obtained deviations between the experimental densities and the obtained ones with the correlation equations versus the temperature for eight isobars (0.1, 20, 40, 60, 80, 100, 120 and 140) MPa. It can be stated that at low pressures the density values are lower than for the higher pressures. Considering the temperature, density values decrease when increasing temperature, as expected.

3.3. Comparison with literature data

For HFE-7300, only one reference which provides density data at atmospheric pressure was found [20]. This reference gives 19 points in our temperature range, from (293.15 – 363.15) K at every 5 K. In order to compare our data with those given by this reference, due to the temperature values are not exactly the same, equations (1) to (3) were used.

The results of the comparison show an AD% = -0.01, an AAD% = 0.03 and a MD% = 0.04, being all the deviation values lower than the combined expanded uncertainty ($\pm 0.07\%$). Figure 3 shows the results of this comparison.

3.4. The derived thermodynamic properties.

The derived properties isothermal compressibility and isobaric expansion data allow the determination of the ability of a given equation not only to correlate PVT data but also to yield the derivatives of V with respect to T or P . Isothermal compressibility, κ_T , describes the effect of pressure on density at a fixed temperature. By differentiating equation (1) respect to the pressure, then equation (9) provides the way to calculate this property:

$$\kappa_T = \left(\frac{1}{\rho} \right) \left(\frac{\partial \rho}{\partial p} \right)_T = \frac{C}{\left(1 - C \ln \left(\frac{B(T) + p}{B(T) + 0.1 \text{MPa}} \right) \right) (B(T) + p)} \quad (9)$$

Table 3 gathers the isothermal compressibility values calculated by using equation (9) in the pressure and temperature ranges considered. Also, Figure 4 shows the κ_T values versus the pressure for the seven isotherms evaluated. It can be stated that for all the isotherms measured, the values of κ_T are increases when the pressure decreases. This statement is in accordance with the assumption that at low pressures the molecules of the fluid are wider apart, so then compressibility takes higher values than when the molecules of the fluid are under pressure, being in this case the molecules closer to each other.

The second derivative property, the isobaric expansion, α_p , which explains how a change in temperature promotes a change in density at a fixed pressure, could also be obtained by differentiating equation (1) taking into account the temperature dependence of $\rho_0(T)$ and $B(T)$:

$$\alpha_p = - \left(\frac{1}{\rho} \right) \left(\frac{\partial \rho}{\partial T} \right)_p \quad (10)$$

Due to the dependence with respect to the temperature of $\rho_0(T)$, some authors [21] and [22] recommend to derive the isobaric expansion from the isobaric densities.

Also, Jaquemin *et al.* [23] reports that differences sometimes found for the values of isobaric expansion in the literature are due not only to differences in density values but also to the fitting equations. Taking this into account, we suppose at each pressure that $\rho_p(T) = a_0 + a_1 T + a_2 T^2$ and consequently $(\partial \rho / \partial T)_p = a_1 + 2a_2 T$. For each pressure we get a set (a_0, a_1, a_2) .

By inserting the differentiated density and the calculated densities $\rho_p(T)$ into $\alpha_p = - (1/\rho)(\partial \rho / \partial T)_p$ the isobaric expansion at the different T, p conditions has been derived:

$$\alpha_p = - \frac{a_1 + 2a_2 T}{a_0 + a_1 T + a_2 T^2} \quad (11)$$

The isobaric expansion values, α_p , in the pressure and temperature ranges investigated are reported in Table 4. Figure 5 shows the variation of α_p versus the temperature for some isobars (0.1, 30, 60, 90, 120 and 140) MPa. It can be seen that when the pressure increases, the values of α_p decrease. Therefore, considering an isobar, the isobaric expansion values at low or medium pressures (0.1 and 30 MPa) are higher when the temperature increases, but at high pressures (from 60 to 140 MPa), when the temperature increases, the values of α_p decrease slightly.

By following these procedures, the isothermal compressibility, κ_T , and the isobaric thermal expansion, α_p , were calculated. Following the EA-4/02 document [12], the estimated uncertainty is 1% for the isothermal compressibility κ_T , and in the order of 3% for the isobaric expansion α_p , as previously reported on similar papers [8], [24, 25] that have used the same methods.

3.5. Speed of sound measurements

Speed of sound, c , is a basic acoustic property. Besides, other thermodynamic properties, such as isentropic compressibility, heat capacity, virial coefficient, and other properties can be derived from it [15]. Table 5 presents the results of the experimental speed of sound measurements, the density values and the isentropic compressibility, κ_S , obtained by means of the Laplace equation (12).

$$\kappa_S = \rho^{-1} \cdot c^{-2} \quad (12)$$

These results can be seen also in Figure 6. As can be observed, the speed of sound can be represented as a linear function in which its value decreases with increasing temperature. On the other hand, isentropic compressibility values increase with increasing temperature. In this case, the function that represents this property is not linear due to the influence of the density, whose change with temperature is also non-linear.

4. Conclusions

A total of 159 experimental high pressure density points were measured for the liquid HFE-7300 within a temperature range (293.15 – 393.15) and in the pressure range (0.1 – 140) MPa. These density measurements suppose a new contribution of data that broadens the scarce physical properties data base available for this fluid. By correlation with a Tait-like equation, the good agreement between the experimental high pressure density data and those calculated was checked, obtaining a maximum deviation MD = 0.05%, being all deviation values below the expanded uncertainty (0.07%). The derived properties, isothermal compressibility and isobaric expansion, were also calculated from the Tait-like equation in the same P , T ranges. Speed of sound at 0.1 MPa and at temperatures from 293.15 to 333.15 K was also measured. Isentropic compressibility was determined from density and speed of sound data.

List of symbols

AAD	Absolute Average Deviation
AD	Average Deviation
a_i	coefficients of isobaric thermal expansion correlation
A_b, B_b, C	coefficients of density correlation
lit	literature
MD	Maximum Deviation
N	number of experimental data points which are in our P, T ranges
P	pressure
T	temperature

Greek letters

σ	Standard deviation
α_p	isobaric thermal expansion
ρ	density
κ_S	isentropic compressibility
κ_T	isothermal compressibility

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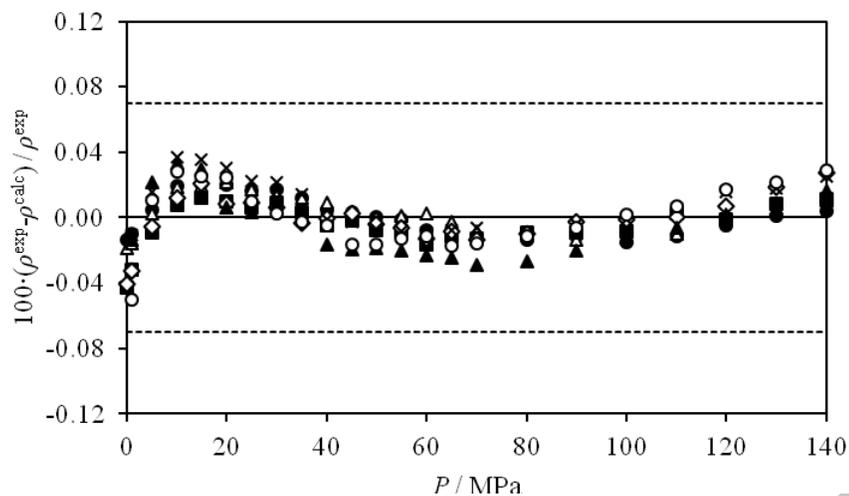
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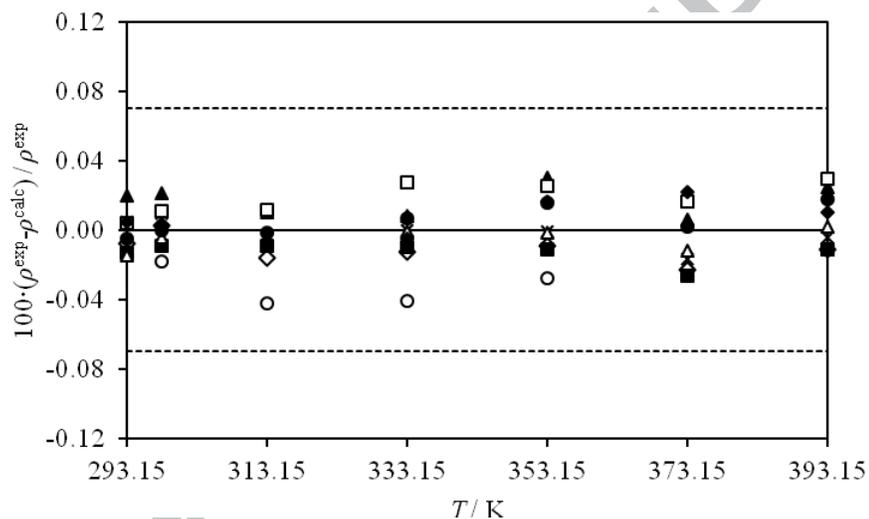
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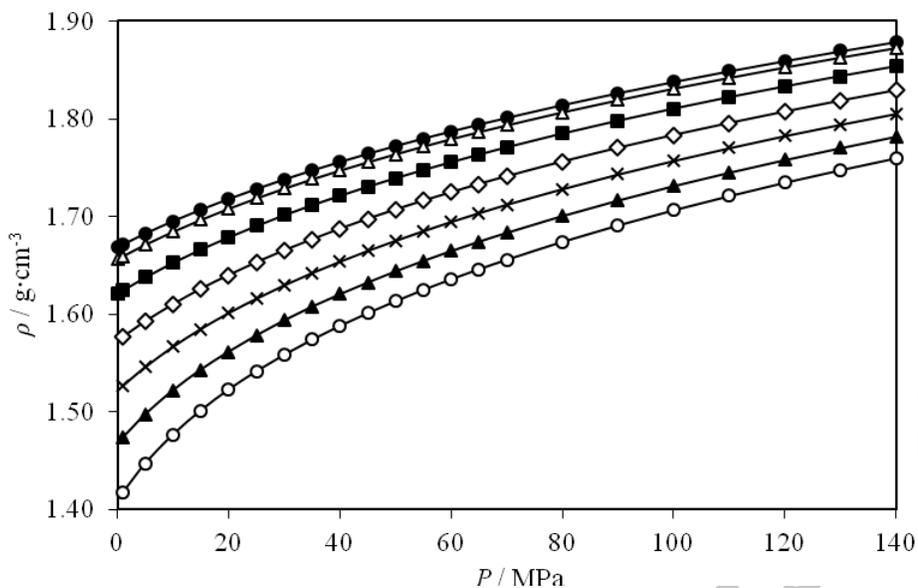


(a)

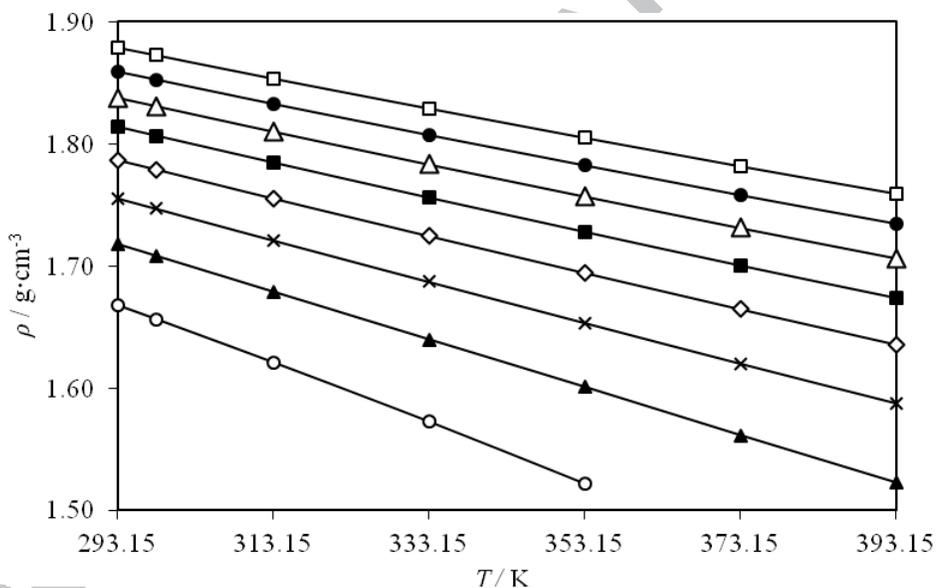


(b)

Figure 1. Deviations between the experimental high pressure density data and those calculated by using the Tait-like equation for HFE-7300 (a) versus the pressure, where: \bullet ; 293.15 K, Δ ; 298.15 K, \blacksquare ; 313.15 K, \diamond ; 333.15 K, \times ; 353.15 K, \blacktriangle ; 373.15 K, \circ ; 393.15 K, and (b) versus the temperature, where: \circ ; 0.1 MPa, \blacklozenge ; 5 MPa, \blacktriangle ; 20 MPa, \times ; 40 MPa, \diamond ; 60 MPa, \blacksquare ; 80 MPa, Δ ; 100 MPa, \bullet ; 120 MPa, \square ; 140 MPa. The dashed lines represent the value of the expanded uncertainty ($0.07\% \text{ g}\cdot\text{cm}^{-3}$).



(a)



(b)

Figure 2. Comparison between experimental density values ρ , and those obtained by the correlation proposed by the Tait-like equation for HFE-7300 (a) versus the pressure at different temperatures, and (b) versus the temperature at several pressures. For (a): \bullet ; 293.15 K, Δ ; 298.15 K, \blacksquare ; 313.15 K, \diamond ; 333.15 K, \times ; 353.15 K, \blacktriangle ; 373.15 K, \circ ; 393.15 K. For (b): \circ ; 0.1 MPa, \blacktriangle ; 20 MPa, \times ; 40 MPa, \diamond ; 60 MPa, \blacksquare ; 80 MPa, Δ ; 100 MPa, \bullet ; 120 MPa, \square ; 140 MPa. The solid line represents the values calculated by equations (1) to (3).

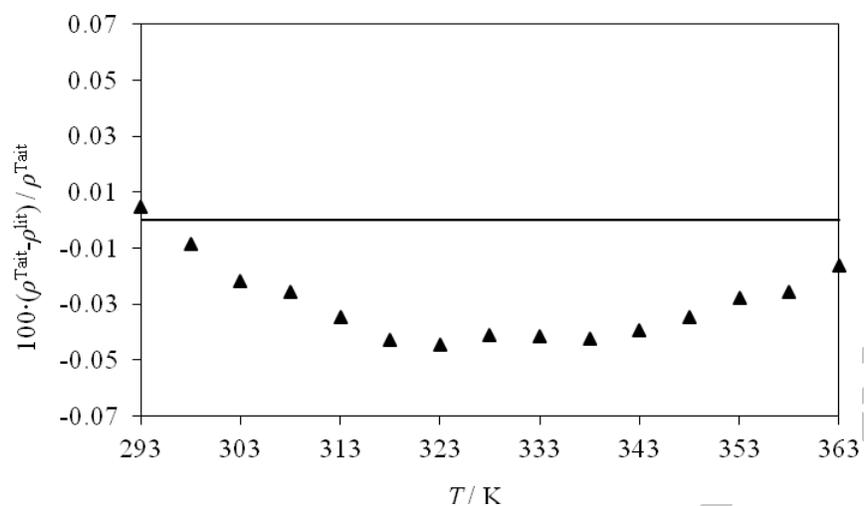


Figure 3. Percentage deviations between the density data obtained in the literature [20], and the values calculated using the Tait-like equation at atmospheric pressure and at several temperatures for the pure fluid HFE-7300.

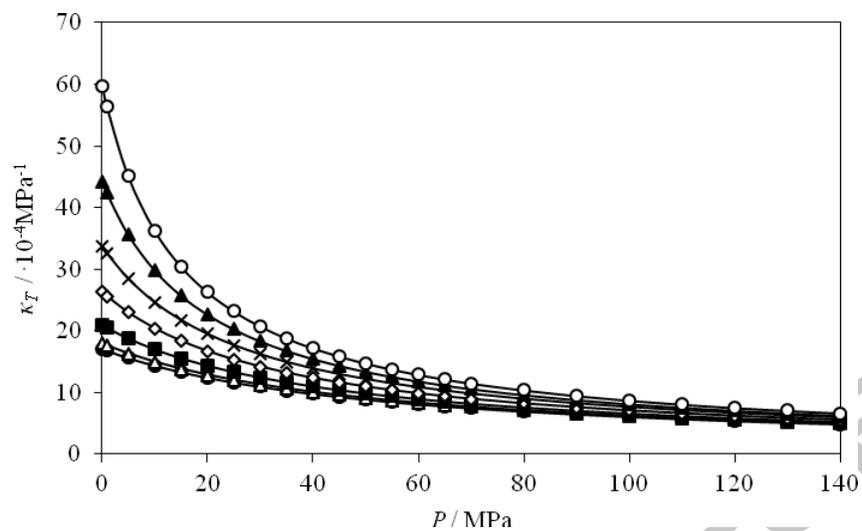


Figure 4. Values of isothermal compressibility κ_T , versus the pressure for the fluid HFE-7300. ●; 293.15 K, △; 298.15 K, ■; 313.15 K, ◇; 333.15 K, ×; 353.15 K, ▲; 373.15 K, ○; 393.15 K.

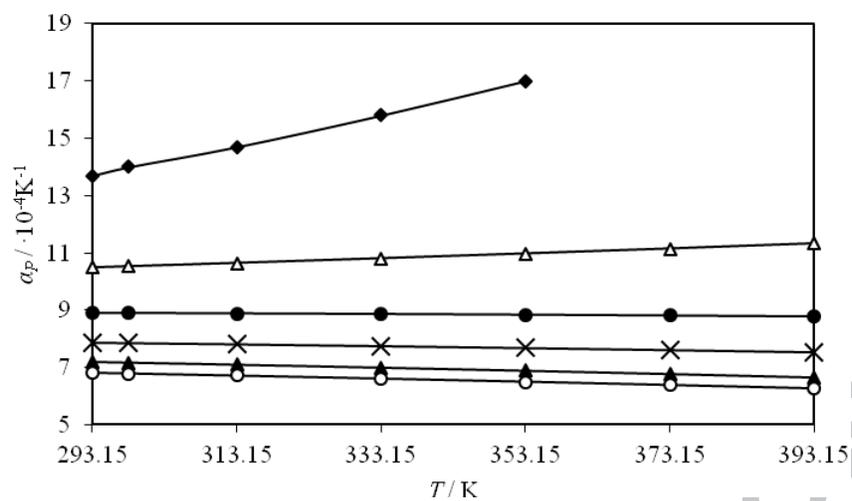


Figure 5. Values of isobaric expansion α_p , versus the temperature for the hydrofluoroether fluid HFE-7300. \blacklozenge ; 0.1 MPa, \triangle ; 30 MPa, \bullet ; 60 MPa, \times ; 90 MPa, \blacktriangle ; 120 MPa, \circ ; 140 MPa.

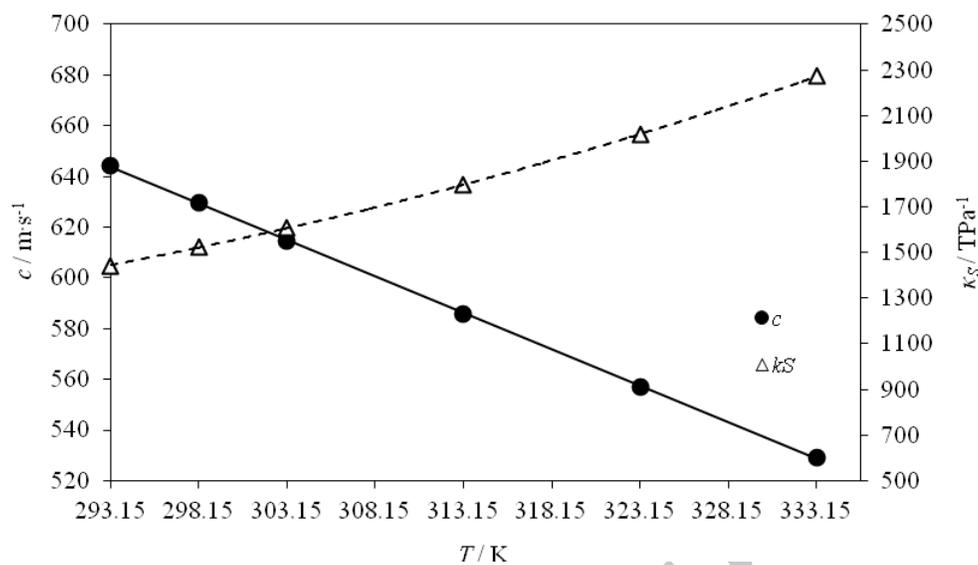


Figure 6. Speeds of sound c , and isentropic compressibilities κ_s , at 0.1 MPa and at several temperatures for the hydrofluoroether fluid HFE-7300.

Table 1. Density values ρ , for the hydrofluoroether fluid HFE-7300 at several pressures and temperatures^a.

P / MPa	T / K						
	293.15	298.15	313.15	333.15	353.15	373.15	393.15
	$\rho / \text{g}\cdot\text{cm}^{-3}$						
0.10	1.6682	1.6567	1.6213	1.5727	1.5217		
1.00	1.6708	1.6594	1.6245	1.5765	1.5265	1.4735	1.4172
5.00	1.6819	1.6710	1.6377	1.5923	1.5456	1.4971	1.4469
10.00	1.6948	1.6844	1.6527	1.6099	1.5665	1.5219	1.4767
15.00	1.7066	1.6966	1.6663	1.6257	1.5847	1.5431	1.5014
20.00	1.7176	1.7080	1.6788	1.6398	1.6010	1.5615	1.5228
25.00	1.7279	1.7186	1.6904	1.6530	1.6158	1.5783	1.5415
30.00	1.7377	1.7286	1.7014	1.6652	1.6295	1.5937	1.5584
35.00	1.7469	1.7381	1.7116	1.6765	1.6421	1.6077	1.5738
40.00	1.7556	1.7471	1.7212	1.6873	1.6537	1.6204	1.5880
45.00	1.7640	1.7556	1.7305	1.6975	1.6648	1.6325	1.6010
50.00	1.7720	1.7638	1.7392	1.7070	1.6752	1.6439	1.6133
55.00	1.7797	1.7717	1.7476	1.7161	1.6851	1.6546	1.6249
60.00	1.7870	1.7793	1.7555	1.7247	1.6945	1.6647	1.6358
65.00	1.7941	1.7865	1.7633	1.7331	1.7035	1.6743	1.6460
70.00	1.8009	1.7934	1.7707	1.7410	1.7121	1.6834	1.6558
80.00	1.8140	1.8067	1.7848	1.7561	1.7281	1.7006	1.6741
90.00	1.8263	1.8191	1.7979	1.7702	1.7431	1.7165	1.6909
100.00	1.8378	1.8310	1.8102	1.7833	1.7570	1.7313	1.7065
110.00	1.8488	1.8420	1.8220	1.7956	1.7701	1.7451	1.7210
120.00	1.8593	1.8527	1.8329	1.8073	1.7825	1.7581	1.7347
130.00	1.8693	1.8628	1.8435	1.8185	1.7941	1.7703	1.7475
140.00	1.8788	1.8725	1.8535	1.8291	1.8052	1.7820	1.7597

^a Estimated expanded uncertainty ($k=2$): temperature $U(T) = 0.03 \text{ K}$, pressure $U(P) = 0.04 \text{ MPa}$, density $U(\rho) = 0.0007 \text{ g}\cdot\text{cm}^{-3}$.

Table 2. Obtained parameters and deviations for density correlation by using equations (1) to (3) for liquid HFE-7300.

$A_0 / \text{g cm}^{-3}$	2.323585
$A_1 / \text{g cm}^{-3} \text{K}^{-1}$	$-2.839676 \cdot 10^{-3}$
$A_2 / \text{g cm}^{-3} \text{K}^{-2}$	$4.253851 \cdot 10^{-6}$
$A_3 / \text{g cm}^{-3} \text{K}^{-3}$	$-7.473361 \cdot 10^{-9}$
B_0 / MPa	296.9519
$B_1 / \text{MPa K}^{-1}$	-1.226653
$B_2 / \text{MPa K}^{-2}$	$1.287132 \cdot 10^{-3}$
C	0.08208861
AAD /(%)	0.01
MD /(%)	0.05
AD /(%)	$-8.41 \cdot 10^{-5}$
$\sigma /(\text{g} \cdot \text{cm}^{-3})$	$2.65 \cdot 10^{-4}$
RMSD /($\text{g} \cdot \text{cm}^{-3}$)	$2.59 \cdot 10^{-4}$

Table 3. Values of isothermal compressibility, κ_T , for HFE-7300 at several pressures and temperatures^a.

P / MPa	T / K						
	293.15	298.15	313.15	333.15	353.15	373.15	393.15
	$\kappa_T \cdot 10^4 / \text{MPa}^{-1}$						
0.10	17.1	17.9	21.0	26.3	33.7		
1.00	16.8	17.6	20.5	25.6	32.6	42.4	56.4
5.00	15.6	16.3	18.8	23.0	28.5	35.7	45.2
10.00	14.4	15.0	17.1	20.4	24.6	29.9	36.3
15.00	13.3	13.9	15.6	18.4	21.7	25.8	30.5
20.00	12.4	12.9	14.4	16.7	19.5	22.7	26.3
25.00	11.6	12.1	13.4	15.4	17.7	20.3	23.2
30.00	11.0	11.3	12.5	14.2	16.2	18.4	20.8
35.00	10.4	10.7	11.7	13.2	14.9	16.8	18.8
40.00	9.8	10.1	11.0	12.4	13.9	15.5	17.2
45.00	9.3	9.6	10.4	11.6	13.0	14.4	15.9
50.00	8.9	9.1	9.9	11.0	12.2	13.4	14.8
55.00	8.5	8.7	9.4	10.4	11.5	12.6	13.8
60.00	8.1	8.3	9.0	9.9	10.8	11.9	12.9
65.00	7.8	8.0	8.6	9.4	10.3	11.2	12.2
70.00	7.5	7.7	8.2	9.0	9.8	10.6	11.5
80.00	7.0	7.1	7.6	8.2	8.9	9.7	10.4
90.00	6.5	6.6	7.1	7.6	8.2	8.9	9.5
100.00	6.1	6.2	6.6	7.1	7.6	8.2	8.7
110.00	5.8	5.9	6.2	6.6	7.1	7.6	8.1
120.00	5.4	5.5	5.8	6.2	6.7	7.1	7.6
130.00	5.2	5.3	5.5	5.9	6.3	6.7	7.1
140.00	4.9	5.0	5.2	5.6	5.9	6.3	6.7

^a Estimated expanded uncertainty ($k=2$): temperature $U(T) = 0.03 \text{ K}$, pressure $U(P) = 0.04 \text{ MPa}$, isothermal compressibility $U(\kappa_T) = 0.001 \kappa_T$.

Table 4. Values of isobaric expansion, α_p , for HFE-7300 at different pressures and temperatures^a.

P / MPa	T / K						
	293.15	298.15	313.15	333.15	353.15	373.15	393.15
	$\alpha_p \cdot 10^4 / \text{K}^{-1}$						
0.10	13.7	14.0	14.7	15.8	17.0		
1.00	13.3	13.6	14.4	15.6	17.0	18.4	20.0
5.00	12.8	13.0	13.6	14.5	15.4	16.4	17.5
10.00	12.3	12.4	12.8	13.4	14.0	14.7	15.4
15.00	11.7	11.8	12.1	12.6	13.0	13.5	14.0
20.00	11.3	11.4	11.6	11.9	12.2	12.5	12.8
25.00	11.0	10.9	11.1	11.3	11.5	11.8	12.0
30.00	10.5	10.5	10.6	10.8	11.0	11.1	11.3
35.00	10.2	10.2	10.3	10.4	10.5	10.6	10.7
40.00	9.9	9.9	9.9	10.0	10.1	10.1	10.2
45.00	9.6	9.6	9.6	9.7	9.7	9.8	9.8
50.00	9.3	9.3	9.3	9.4	9.4	9.4	9.4
55.00	9.2	9.2	9.3	9.3	9.3	9.3	9.3
60.00	8.9	8.9	8.9	8.9	8.8	8.8	8.8
65.00	8.7	8.7	8.7	8.6	8.6	8.6	8.5
70.00	8.5	8.5	8.5	8.4	8.4	8.3	8.3
80.00	8.2	8.2	8.1	8.1	8.0	7.9	7.9
90.00	8.0	7.8	7.8	7.7	7.7	7.6	7.5
100.00	7.6	7.6	7.5	7.5	7.4	7.3	7.2
110.00	7.4	7.3	7.3	7.2	7.1	7.0	6.9
120.00	7.2	7.2	7.1	7.0	6.9	6.8	6.7
130.00	7.0	7.0	6.9	6.8	6.7	6.6	6.5
140.00	6.8	6.8	6.7	6.6	6.5	6.4	6.3

^a Estimated expanded uncertainty ($k=2$): temperature $U(T) = 0.03 \text{ K}$, pressure $U(P) = 0.04 \text{ MPa}$, isobaric expansion $U(\alpha_p) = 0.003 \alpha_p$.

Table 5. Experimental speed of sound, c , and density, ρ , obtained at 0.1 MPa by using the Anton Paar DSA 5000 density and speed of sound meter, calculated isentropic compressibility, κ_S , and average deviations between experimental density data and literature values [17] for HFE-7300^a.

T / K	$c / \text{m}\cdot\text{s}^{-1}$	$\rho / \text{g}\cdot\text{cm}^{-3}$	$\kappa_S / \text{TPa}^{-1}$	AD%
293.15	644.50	1.66843	1443	$1.85\cdot 10^{-3}$
298.15	629.44	1.65679	1523	$1.54\cdot 10^{-3}$
303.15	614.76	1.64511	1608	$1.78\cdot 10^{-3}$
313.15	585.65	1.62141	1798	$1.72\cdot 10^{-3}$
323.15	557.04	1.59704	2018	$1.66\cdot 10^{-2}$
333.15				$-6.36\cdot 10^{-3}$
	529.01	1.57280	2272	³

^a Estimated expanded uncertainty ($k = 2$): temperature $U(T) = 0.01 \text{ K}$, speed of sound $U(c) = 1 \text{ m}\cdot\text{s}^{-1}$, pressure $U(P_{0.1}) = 10^{-4} \text{ MPa}$, density $U(\rho) = 9\cdot 10^{-4} \text{ g}\cdot\text{cm}^{-3}$, isentropic compressibility $U(\kappa_S) = 0.50\kappa_S$.

Highlights

- > New density data for the compound HFE-7300
- > The pressure and temperature intervals are 0.1 – 140.0 MPa and 298.15 – 393.15 K
- > 159 data were used to fit the coefficients of a Tait-like equation
- > The isobaric expansivity and the isothermal compressibility have been derived
- > The speed of sound of pure HFE-7300 at 0.1 MPa and up to 333.15 K are reported

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