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Density Data for the Refrigerant Ethyl Fluoride (HFC-161) over a Temperature Range from (230 to 344) K

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ABSTRACT: Density data of the refrigerant ethyl fluoride (HFC-161) have been measured in the range of temperatures from (230 to 344) K. Liquid density experimental data of HFC-161 are correlated by the VDNS-type and the modified Rackett-type density equations, and the parameters of the density equations are given. The correlated results show that they have a good agreement with the experimental data. The average relative deviation of liquid density from the VDNS-type density equation and from the modified Rackett-type density equation are 0.11 % and 0.09 %, respectively. In addition, the Peng−Robinson (PR) equation of state is also correlated to calculate the liquid density for HFC-161. The average relative deviation and maximum relative deviation from the PR equation are 1.26 % and 5.15 %, respectively, which are a little larger than those from the VDNS-type and the modified Rackett density equations. However, the vapor density results have been supplied with the PR equation.

INTRODUCTION

Economic, energy, and environmental developments are necessary facets of a strategy for sustainable development in the 21st century. Refrigeration and cryogenics were important parts of energy technologies in the 20th century, and they have undergone unprecedented development and applications. However, it is very difficult for traditional technologies of refrigeration and cryogenics to meet the requirements of sustainable development of the world; in particular, alternative refrigerant technologies are facing severe challenges.

To protect the ozone layer from atmospheric ozone-depleting substances in the Montreal Protocol, many countries have developed alternative refrigerants to chlorodifluoromethane (HCFC-22) and R502. The trend is toward the development of ozone depletion potential (ODP) = 0 refrigerants. Knowing such refrigerants as HCFC-22, R502 must be phased out; studies showed it was hard to find pure substances as viable alternatives, and there is an urgent need for the development of refrigerant mixtures. Many researchers have examined the use of R407C, R410A, and R404A, and they have suggested the use of R410A in domestic air conditioners, the use of R407C in large and medium-sized refrigeration and air-conditioning systems, and the use of R404A in commercial refrigeration systems, such as supermarket stores, industrial refrigeration, and transport refrigeration.[1−3] But the global warming potential (GWP) of these mixtures still is high, which makes it difficult for them as the long-term substitutes. Therefore, it is very important to find more outstanding environmental performance alternatives for the long term, and the study of the new types of refrigerants is currently an urgent topic.

We know that the new refrigerants should meet some reasonable requirements.[4] After several years of study, it has been found that ethyl fluoride (HFC-161) is a very promising alternative refrigerant for its many valuable advantages, such as zero ODP, a very low GWP, large volumetric cooling capacity, and high COP. Therefore, the research on the thermophysical properties of HFC-161 is very necessary for energy saving and global environment protection. Some research on HFC-161 was done.[4−11] But the density data for refrigerant HFC-161 are few in the existing literature. In this work, the density data for HFC-161 in the temperature range from (230 to 344) K are measured, and its density equation is given; this will be very important for promoting its applications in the actual refrigeration system.

EXPERIMENTS

The samples of HFC-161, provided by Zhejiang Lantian Environment Protection Hi-Tech Co., Ltd., has a purity of 99.74 wt % with the principal impurities of ethylene and isobutane. Chlorodifluoromethane (HCFC-22) was provided by Honeywell corporation with a minimum purity of 0.999 (mass fraction). No further purification was done on these chemicals before use.

Data of temperature−pressure−liquid density ($T-p-\rho_L$) were obtained from an experiment equipment with a recirculation still. A schematic of the experimental equipment in this work is shown in Figure 1. It consists of a stainless steel equilibrium cell and temperature and pressure measuring systems, and so forth. A motor blender, rotated at variable speeds, is used to accelerate the equilibrium process. The temperature of the equilibrium cell in the thermostatted bath is maintained by an autocascaded compression refrigeration system and a heating coil. The temperature fluctuation in the bath is less than ± 5 mK/30 min. The temperature is measured by a four-head 25-platinum resistance thermometer (model: WZPB-I, China) with an uncertainty of ± 1 mK (ITS) and a Keithley 2001 data acquisition/switch unit. The overall uncertainty of temperature measured is within ± 10 mK. The pressure is measured by a pressure transducer (model: PMP4010, Drunk). The total uncertainty of the pressure measurement is within ± 1.2 kPa.

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Table 1. Experimental Data of the Refrigerant HCFC-22 within the Temperature Range of (230 to 310) K

T	p	p_{ref}	$\lvert p - p_{\mathrm{ref}}\rvert/p_{\mathrm{ref}}$	ρ_{L}	ρ_{ref}	$\lvert\rho_{\mathrm{L}} - \rho_{\mathrm{ref}}\rvert/\rho_{\mathrm{ref}}$
K	Pa	Pa	%	kg·m^{-3}	kg·m^{-3}	%
237.03	125481	125600	0.09	1396.9	1395.4	0.11
242.05	156524	156410	0.07	1380.6	1380.5	0.01
248.23	202411	202080	0.16	1361.7	1361.7	0.00
250.79	223862	223770	0.04	1352.0	1353.9	0.14
257.12	285601	285110	0.17	1333.2	1334.1	0.07
262.27	343762	343880	0.03	1317.7	1317.6	0.00
267.03	405649	406020	0.09	1302.2	1302.0	0.01
272.37	485714	485470	0.05	1283.6	1284.2	0.05
276.67	558121	557540	0.10	1268.9	1269.5	0.05
283.21	682584	682180	0.06	1245.0	1246.5	0.12
287.52	774369	774990	0.08	1231.0	1230.9	0.01
294.06	932294	933380	0.12	1206.2	1206.4	0.02
298.34	1047703	1049300	0.15	1188.9	1189.9	0.08
303.44	1201858	1200900	0.08	1168.1	1169.6	0.13
306.98	1316368	1315300	0.08	1156.7	1155.0	0.15

Table 2. Experimental Data of the Refrigerant HFC-161 within the Temperature Range of (230 to 344) K

T	p	ρ_{L}	T	p	ρ_{L}
K	Pa	kg·m^{-3}	K	Pa	kg·m^{-3}
231.49	83130	822.4	290.50	736602	713.5
234.21	94431	817.1	293.49	801346	706.5
236.99	107290	812.3	296.62	874826	700.0
239.38	119324	807.8	298.35	917133	696.2
242.26	135315	802.9	301.40	996401	689.8
244.45	148503	798.9	303.42	1050982	685.1
247.17	166356	794.5	305.56	1111432	680.2
249.55	183202	790.1	308.36	1195092	674.0
252.04	202063	785.0	311.02	1278681	667.9
254.66	223938	781.2	313.56	1362714	662.0
256.86	243509	777.4	316.06	1439187	655.9
259.79	271615	772.4	318.06	1511097	651.0
261.53	289323	769.2	320.34	1596466	645.2
264.92	326523	763.0	322.83	1683768	638.8
267.46	356626	758.2	325.41	1800764	632.2
270.02	389015	753.3	328.04	1922450	625.0
272.57	423544	748.5	330.58	2035850	617.8
275.14	460686	743.7	332.88	2105827	609.1
277.69	499681	738.5	335.61	2262541	599.5
280.25	542231	734.5	337.83	2369888	591.6
282.93	587975	728.1	340.19	2489540	583.4
285.36	633635	724.3	343.01	2639040	573.3
288.87	701868	716.0			

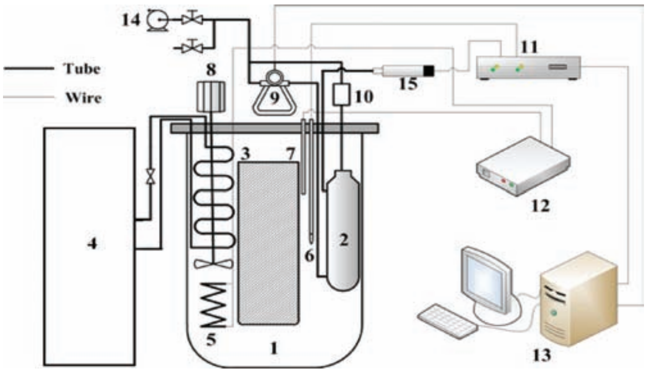

Figure 1. Experimental apparatus of the refrigerant density; 1, thermostatted bath; 2, vessel; 3, cooling coil; 4, autocascade refrigeration system; 5, heating coil; 6, high accuracy PT thermometer; 7, thermometer; 8, stirrer; 9, mass flowmeter; 10, micropump; 11, Kelthley 2001 data collector; 12, high accuracy temperature controller; 13, PC; 14, vacuum pump; 15, high accuracy pressure transducer.

The liquid density is measured by the mass flowmeter (model: CMF025, EMERSON), and its principle is that, when there is a mass flow in a rotating tube, the mass flow will exert a force to the tube. The force is so-called Coriolis force by the vibration of the tube. The natural vibration frequency of the flow tubes depends on the combined mass of the tube and the fluid contained in it. By setting the tube in motion and measuring the natural frequency, the mass of the fluid contained in the tube can be deduced. Dividing the mass on the known volume of the tube gives us the density of the fluid. The total uncertainty of the density measurement in Tables 1 and 2 is within ± 0.5 kg·m^{-3}.

The experimental processes are as follows. The cell was evacuated to remove the inert gases. A targeted amount of HFC-161 was introduced into the cell, and the temperature of the entire system was maintained by controlling the temperature of the thermostatted bath. The vapor in the cell was circulated continuously by the magnetic circulation pump until an equilibrium state was established. It was believed that 2 h or more was sufficient to obtain thermal equilibrium state between the cell and the thermostatted bath. After the desired temperature was attained, the pressure and liquid density in the equilibrium cell were measured by the pressure transducer and the mass flowmeter, respectively.

Before the experiment for refrigerant HFC-161, the experimental data (T−p−ρ_{L}) of the refrigerant HCFC-22 are

Table 3. Correlated Results of the Refrigerant HFC-161 by using Equations 1 and 3 and the PR Equation within the Temperature Range of (230 to 344) K

	eq 1		eq 3		PR				
	ρ_{calL}		ρ_{calL}		ρ_{calL}		ρ_{calV}	p_{cal}	
T/K	$\text{kg}\cdot\text{m}^{-3}$	$\delta\rho\%$	$\text{kg}\cdot\text{m}^{-3}$	$\delta\rho\%$	$\text{kg}\cdot\text{m}^{-3}$	$\delta\rho\%$	$\text{kg}\cdot\text{m}^{-3}$	Pa	$\delta\rho\%$
231.49	822.7	0.03	820.9	0.18	822.9	0.06	2.2	86836	4.46
234.21	817.5	0.06	816.4	0.08	818.9	0.22	2.5	98008	3.79
236.99	812.4	0.01	811.8	0.06	814.6	0.29	2.8	110613	3.10
239.38	808.0	0.03	807.8	0.00	810.9	0.39	3.1	122422	2.60
242.26	802.8	0.01	802.9	0.01	806.4	0.44	3.4	137981	1.97
244.45	798.8	0.01	799.2	0.04	802.8	0.49	3.7	150870	1.59
247.17	794.0	0.06	794.5	0.01	798.4	0.49	4.1	168220	1.12
249.55	789.8	0.04	790.4	0.04	794.4	0.54	4.5	184580	0.75
252.04	785.4	0.05	786.1	0.14	790.2	0.66	4.9	203102	0.51
254.66	780.8	0.06	781.5	0.04	785.6	0.57	5.4	224098	0.07
256.86	776.9	0.07	777.6	0.02	781.8	0.56	5.8	243069	0.18
259.79	771.7	0.09	772.4	0.00	776.5	0.53	6.4	270288	0.49
261.53	768.6	0.08	769.2	0.01	773.3	0.54	6.8	287563	0.61
264.92	762.5	0.06	763.1	0.01	767.0	0.53	7.6	323639	0.88
267.46	758.0	0.03	758.4	0.03	762.1	0.52	8.2	352896	1.05
270.02	753.3	0.00	753.6	0.05	757.1	0.51	8.9	384496	1.16
272.57	748.6	0.02	748.8	0.05	752.0	0.47	9.7	418256	1.25
275.14	743.8	0.02	744.0	0.04	746.8	0.42	10.5	454387	1.37
277.69	739.0	0.08	739.0	0.08	741.5	0.41	11.3	492763	1.38
280.25	734.1	0.05	734.0	0.06	736.0	0.21	12.2	533747	1.56
282.93	728.9	0.12	728.7	0.09	730.2	0.29	13.2	579489	1.44
285.36	724.1	0.02	723.9	0.06	724.8	0.07	14.2	623647	1.58
288.87	717.1	0.15	716.7	0.10	716.7	0.10	15.7	691791	1.44
290.50	713.7	0.03	713.4	0.02	712.9	0.08	16.5	725373	1.52
293.49	707.5	0.14	707.1	0.09	705.7	0.10	18.0	790408	1.36
296.62	700.8	0.12	700.4	0.06	698.0	0.28	19.6	863151	1.33
298.35	697.1	0.13	696.6	0.07	693.7	0.36	20.6	905502	1.27
301.40	690.3	0.08	689.9	0.02	685.7	0.58	22.4	984285	1.22
303.42	685.7	0.09	685.4	0.04	680.4	0.69	23.7	1039140	1.13
305.56	680.8	0.09	680.5	0.04	674.6	0.83	25.1	1099874	1.04
308.36	674.2	0.04	674.0	0.00	666.8	1.07	27.0	1183750	0.95
311.02	667.8	0.00	667.6	0.03	659.1	1.31	29.1	1267801	0.85
313.56	661.6	0.06	661.5	0.08	651.6	1.57	31.1	1352293	0.76
316.06	655.3	0.09	655.2	0.10	644.0	1.82	33.2	1439996	0.06
318.06	650.2	0.13	650.2	0.13	637.8	2.03	35.1	1512924	0.12
320.34	644.1	0.17	644.2	0.16	630.4	2.30	37.3	1600067	0.23
322.83	637.5	0.21	637.6	0.19	622.2	2.60	39.8	1699150	0.91
325.41	630.4	0.29	630.5	0.26	613.4	2.97	42.6	1807035	0.35
328.04	622.9	0.34	623.1	0.31	604.1	3.35	45.7	1922306	0.01
330.58	615.5	0.38	615.7	0.34	594.8	3.73	48.9	2039332	0.17
332.88	608.6	0.09	608.8	0.05	586.1	3.79	52.0	2149965	2.10
335.61	600.2	0.11	600.3	0.13	575.3	4.04	55.9	2287074	1.08
337.83	593.1	0.25	593.1	0.25	566.2	4.30	59.4	2404214	1.45
340.19	585.4	0.34	585.2	0.32	556.2	4.66	63.3	2532972	1.74
343.01	575.7	0.43	575.4	0.37	543.7	5.15	68.5	2694605	2.11

measured to verify the reliability of the experimental apparatus. The experimental results are shown in Table 1. In Table 1, p_{ref} is the pressure from the literature,[12] ρ_{L} is the liquid density and ρ_{ref} is the liquid density from the literature.[12]

From Table 1, it can be seen that the experimental results have a good agreement with the results in literature.[12] The average relative pressure deviation is 0.09 %, and the average relative density deviation is 0.06 %.

The experimental data $(T-p-\rho_{\text{L}})$ of the refrigerant HFC-161 are listed in Table 2. In Table 2, the pressure is the one in the vapor–liquid equilibrium state of the system.

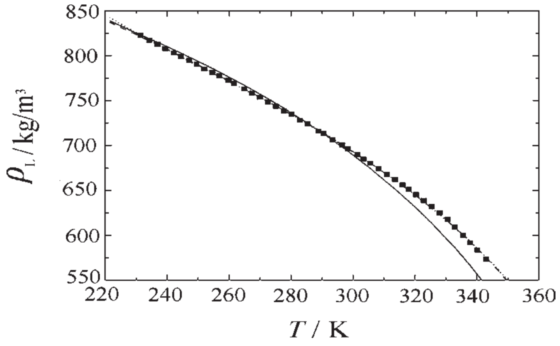

Figure 2. Temperature−density diagrams of the refrigerant HFC-161 by using the VDNS-type equation, the modified Rackett-type equation, and the PR equation; ■, experimental data; · · ·, VDNS-type equation; - - -, modified Rackett-type equation; —, PR equation.

Table 4. Parameters of Equations 1 and 3 and the PR Equation

parameters	eq 1	eq 3	PR
B_1	2.2811		
B_2	5.9884		
B_3	−22.0014		
B_4	27.1041		
C_1		0.1734	
C_2		−0.2192	
C_3		−1.0116	
a_1			−0.00193
a_2			1.58613
b_1			0.0000471

MODEL

Usually, the VDNS-type [eq 1][13] and Rackett-type [eq 2][14] equations are used to correlated the saturated liquid density.

$$\rho_r = 1 + B_1\tau^{0.35} + B_2\tau^2 + B_3\tau^3 + B_4\tau^4 \tag{1}$$

$$\rho_r = Z_c^{-\tau^{2/7}} \tag{2}$$

where $\rho_r = \rho/\rho_c$, B_1, B_2, B_3, and B_4 are parameters of eq 1, $T_r = T/T_c$, and Z_c is a critical compressibility factor.

Equation 2 was first proposed in 1970 for its high accuracy. Later, Spencer et al.[15] and Campbell et al.[16] developed the revised Rackett-type equations in 1972 and 1985, respectively. In this paper, we developed it to the new form according to the Rackett-type equation; that is, a third parameter is employed to promote the correlation precision. The expression of the modified Rackett equation is

$$\rho_r' = (C_1 + C_2\tau)^{-(C_3 + \tau^{2/7})} \tag{3}$$

where $\rho_r' = \rho/(p_c/(RT_c))$; C_1, C_2, and C_3 are the parameters of eq 3.

Therefore, we will use eqs 1 and 3 to correlate the experimental data in this work.

RESULTS AND DISCUSSION

For the correlation of the experimental data, a computer program has been developed applying the least-squares method for fitting an objective function. The objective function using eqs 1 and 3 is

$$\mathrm{OF} = \frac{1}{Np}\sum_j^{Np}\left(\frac{\rho_{\mathrm{exp\ L}} - \rho_{\mathrm{calL}}}{\rho_{\mathrm{exp\ L}}}\right)_j^2 \tag{4}$$

where ρ_{expL} is the experimental liquid density and ρ_{calL} is the calculated liquid density.

The correlated results are shown in Tables 2 and 3 and Figure 2. The deviations, $\delta\rho\%$, are defined as follows

$$\delta\rho\% = |(\rho_{\mathrm{cal}} - \rho_{\mathrm{exp}})/\rho_{\mathrm{exp}}| \cdot 100 \tag{5}$$

From the results in Table 3 and Figure 2, it can be seen that, within a wide range of temperatures and pressures, the results correlated by eqs 1 and 3 show a good agreement with existing experimental data, the average relative deviation of liquid density from eq 1 is 0.11 %, and the average derivation of liquid density from eq 1 is 0.09 %. The results correlated by eq 3 are slightly superior to those from eq 1. The parameters of eqs 1 and 3 are shown in Table 3.

In addition, we have used the Peng−Robinson[17] (PR) equation of state to correlate the density. Its expression is

$$p = \frac{RT}{v - b} - \frac{a}{v^2 + 2vb - b^2} \tag{6}$$

$$a = a_1T + a_2 \tag{7}$$

$$b = b_1 \tag{8}$$

where p is the pressure, v is the molar volume, T is the absolute temperature, R is general gas constant, a and b are PR equation of state dependent parameters, respectively, and a_1, a_2, b_1 are the parameters of eqs 7 and 8, respectively.

The objective function using eq 6 is

$$\mathrm{OF} = \frac{1}{Np}\sum_j^{Np}\left(\left(\frac{p_{\mathrm{exp}} - p_{\mathrm{cal}}}{p_{\mathrm{exp}}}\right)_j^2 + \left(\frac{\rho_{\mathrm{expL}} - \rho_{\mathrm{calL}}}{\rho_{\mathrm{expL}}}\right)_j^2\right) \tag{9}$$

where p_{exp} is the experimental pressure and p_{cal} is the calculated pressure.

The deviations, $\delta p\%$, in Table 3 are defined as follows

$$\delta p\% = |(p_{\mathrm{cal}} - p_{\mathrm{exp}})/p_{\mathrm{exp}}| \cdot 100 \tag{10}$$

Results obtained by the PR equation are shown in Table 3, and the parameters of the PR equation are given in Table 4. From Table 3, it can be seen that the deviations from the PR equation are the largest among three equations. The average relative deviation from the PR equation is 1.26 %, and its maximum relative deviation is 5.15 %. Though the deviation from the PR equation is a little large, the vapor density of HFC-161 can be calculated easily with the PR equation. The calculated results are shown in Table 3.

CONCLUSIONS

In this paper, the density of the refrigerant HFC-161 is investigated in the ranges of temperatures from (230 to 344) K. Liquid density experimental data of HFC-161 are correlated by the VDNS-type and the modified Rackett density equations, and the parameters of the density equations are given. The correlated results show that they have a good agreement with the experimental data; the average relative deviation of liquid density from the VDNS-type density equation and from the modified Rackett density equation are 0.11 % and 0.09% , respectively. In addition, the PR equation of state is also correlated to calculate the liquid density for HFC-161. The average relative deviation and maximum relative deviation from the PR equation are 1.26 % and 5.15 %, respectively, which are a litter larger than those from the VDNS-type and the modified Rackett density equations. Meanwhile, the vapor density results have been supplied with the PR equation. These will have a good basis for the actual applications of the refrigerant HFC-161.

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