Gaseous Pressure−Volume−Temperature Properties of 1,1,1,2,3,3,3-Heptafluoropropane

Lin Shi, Yuan-Yuan Duan,* Ming-Shan Zhu, and Li-Zhong Han

Department of Thermal Engineering, Tsinghua University, Beijing 100084, People's Republic of China

Xia Lei

Beijing United University, Beijing 100054, People's Republic of China

One-hundred and forty-one pressure-volume-temperature data points for 1,1,1,2,3,3-heptafluoropropane (HFC-227ea) in the gaseous phase have been measured using Burnett/isochoric methods. Burnett expansion measurements were made both at 363.15 K and at 318.15 K. On the basis of the pressure-density relationships established at 363.15 K and 318.15 K, data were collected along nine isochores for temperatures from 283 to 377 K and pressures from 0.26 to 2.5 MPa. The maximum temperature uncertainty and maximum pressure uncertainty in this work were estimated to be within ±10 mK and ±500 Pa, respectively. On the basis of the present data and results from the literature, the parameters of a virial equation of state were determined to represent the gaseous thermodynamic properties of HFC-227ea. The purity of the sample used in this work is 99.9 mol %.

Introduction

The expected worldwide ban on many low-molar-mass chlorofluorocarbons has prompted a vigorous search for alternatives with zero ozone-depletion potential (ODP) and lower global-warming potential (GWP). 1,1,1,2,3,3,3-Heptafluoropropane (HFC-227ea) has zero ODP. It is a recently introduced, commercially available hydrofluorocarbon (HFC) useful in fire suppression, refrigeration, sterilization, and propellant applications. It can be used as an alternative to halon, and blends containing HFC-227ea are potential alternatives to HCFC-22 and R502. Effective use of HFC-227ea requires that the thermodynamic and transport properties be accurately measured, but there is very little data available. Wirbser et al. (1992) measured the specific heat capacity and Joule−Thomson coefficient of HFC-227ea; Salvi-Narkhede et al. (1992) measured the vapor pressure, liquid molar volumes, and ciritical properties; Park (1993) measured the gaseous pressure-volume-temperature (PVT) properties with a Burnett apparatus at five temperatures; Klomfar et al. (1994) measured the liquid PVT properties; Robin (1994) listed the thermophysical properties of HFC-227ea including estimated transport properties; Defibaugh and Moldover (1997) measured the liquid PVT behavior and the saturated liquid density; Weber (1998) measured the vapor pressure of HFC-227ea; Laesecke and Hafer (1998) measured the viscosity of HFC-227ea with a coiled capillary viscometer at low temperature and a straight capillary viscometer at high temperature; Pátek et al. (1998) measured PVT properties of HFC-227ea with a Burnett apparatus at temperatures of 393 K and 423 K; Shi et al. (1999) measured the vapor pressure; Liu et al. (1999a; b) measured the saturated liquid viscosity and gaseous thermal conductivity.

This paper reports the experimental results of gaseous PVT properties of HFC-227ea. On the basis of these data and results of literature, parameters of a virial equation of state for HFC-227ea were determined.

Experimental Section

Materials. The sample of HFC-227ea was obtained from Shanghai Huiyou Chemical Corp., China, and was used without further purification. The manufacturer stated that the water content was less than 20 ppm. For the gas chromatographic analysis, the purity of the sample was better than 99.9 mol %. The sample of helium used for calibration was obtained from Beijing Huanyuan Gas Chemical Corp., China. The manufacturer stated that the sample purity was better than 99.99 mol %, the impurity being hydrogen, and was used without further purification.

Apparatus. A modified Burnett apparatus was used in this work, which was described previously (Zhu et al., 1992; Fu et al., 1995; Duan et al., 1997), will be introduced briefly here and any modification will be noted. The schematic of the entire measuring system is shown in Figure 1. It includes a high-accuracy thermostat bath, a temperature-measurement system, a pressure-measurement and control system, a vacuum system, and a sample cell.

The temperature of the thermostat bath can be varied from 223 to 453 K. The temperature instability is less than ±2 mK in 1 h, and less than ±5 mK in 8 h. Silicone oil, distilled deionized water, or alcohol can be used as the fluid in the bath, depending on the temperature range. The temperature-measurement system includes the platinum resistance thermometers (Tinsley: 5187SA) with an uncertainty of ±2 mK, a precision thermometer bridge (Tinsley: 5840D) with an accuracy within ±1 mK, a select switch (Tinsley: 5840CS/6T), and a personal computer. The maximum overall temperature uncertainty for the bath and

---

* To whom correspondence should be addressed. E-mail: yyduan@te.tsinghua.edu.cn.

10.1021/je9901334 CCC: $18.00

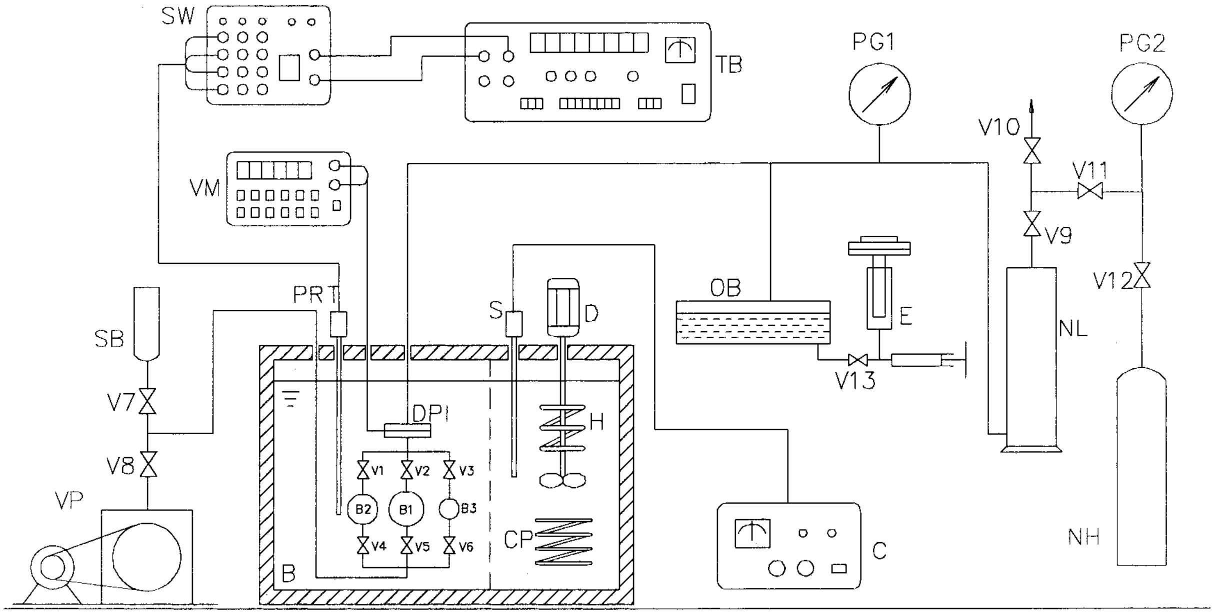

Figure 1. Experimental apparatus: (B) thermostat bath, (B1) sample vessel (1000 mL), (B2) sample vessel (600 mL), (B3) sample vessel (200 mL); (C) temperature controller, (CP) cooler, (D) stirrer, (DPI) differential pressure detector, (E) oil piston type pressure gage, (H) heater, (NH) N_2 bottle, (NL) pressure damper, (OB) oil-gas separator, (PG1, PG2) pressure gage, (PRT) platinum resistance thermometer, (S) temperature sensor, (SB) sample bottle, (SW) selector switch, (TB) thermometer bridge, (V1−V13) valves, (VM) digital multimeter, and (VP) vacuum pump.

the temperature-measurement system was less than ±10 mK. The temperatures were determined on the International Temperature Scale of 1990 (ITS-90).

The pressure-measurement system can measure pressure in the range of 0.001 to 6 MPa; it includes a piston-type pressure gauge, a pressure transducer, and a digital pressure gauge. A sensitive diaphragm pressure transducer (Xi'an Instrument: 1151DP) separated the sample in the thermostat bath from nitrogen which transmitted the pressure outside the bath. The accuracy of the transducer is 0.25%, the pressure difference adjustable range is 6 to 38 kPa, the temperature range is 233 to 378 K, and the maximum allowable pressure is 14 MPa. The accuracy of the digital pressure gauge is 0.05% and the pressure range is 1 to 160 kPa. When the pressure is below 160 kPa, the nitrogen transmitted the sample pressure directly to the digital pressure gauge, so the pressure measurement system has a maximum uncertainty of ±200 Pa. Pressure above 160 kPa is measured with a piston-type pressure gauge, and the accuracy of the piston-type pressure gauge is 0.005% in the pressure range of 0.04 to 6 MPa, while the atmospheric pressure is measured with the digital pressure gauge, and the uncertainty was estimated to be less than ±500 Pa. The extremely high vacuum is about 1.3×10^{-4} Pa.

Procedure. The sample cells are three heavy-walled vessels, which were made of 1Cr18Ni9Ti stainless steel. Two cells (B2 and B3 in Figure 1) separated by a valve were used in the present work; the inner volumes were $V_1 = 600$ mL and $V_2 = 200$ mL, respectively.

Before the experiment, the sample cell was rinsed with acetone to remove any residue from previous experiments and was purged several times with the sample gas. After the sample cell B2 (inner volume, $V_1 = 600$ mL) was filled, the temperature of the thermostat bath was controlled at the experimental temperature. When thermal equilibrium was established between the sample and the heat-transfer fluid in the bath and the pressure remained constant, the temperature and the pressure of the sample were measured. Meanwhile, the sample cell B3 (inner volume, $V_2 =$ 200 mL) was evacuated by means of an oil diffusion pump to about 1.3×10^{-3} Pa. After the temperature and the initial pressure P_0 were measured, the expansion valve was opened, permitting pressure equalization between the two vessels. When thermal equilibrium had been restored, the expansion valve was closed and a new pressure P_1 and the temperature were measured. The evacuation, expansion, and measurement were repeated to obtain a series of isothermally measured pressures P_0, P_1, ..., P_{i-1}, P_i.... The series of pressures was related by a nearly constant ratio of volumes. The densities were calculated utilizing a virial equation of state without requiring direct measurement of the mass or inner volume.

After the pressure−density relationships were established at Burnett expansion temperatures, data were collected along isochores. The pressure measurement for each of the isochores at Burnett expansion temperatures was used to determine the density.

Calibration with Helium

The apparatus constant can be expressed as the ratio of the total volume of the two cells to one volume of the first cell:

$$N = \frac{V_1 + V_2}{V_1} \tag{1}$$

where N is the apparatus constant and V_1 and V_2 are the respective volumes of sample cell B2 and B3 in the present work. The sample cells are thick-walled metal vessels and the maximum pressure was less than 2.5 MPa in this work, so the pressure distortion of the cell is negligible. Because the volume of the cell varies linearly with temperature changes in the apparatus, the volume ratio N is a constant in this work.

Helium is well-suited as the calibration gas for the Burnett apparatus. Burnett expansions of helium were made at 317.65 K and 331.35 K to determine the apparatus constant, N. From established principles of the Burnett

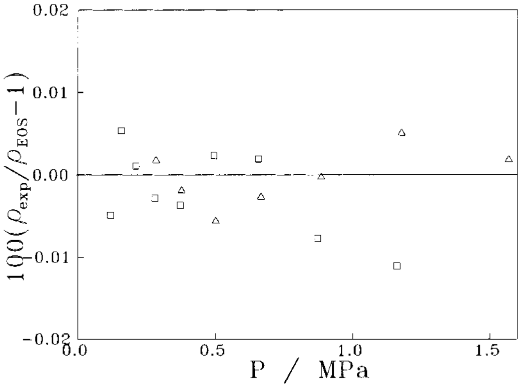

Figure 2. Deviations of experimental density from an equation of state (Angus et al., 1977) vs pressure for helium: (□) $T = 317.65$ K isotherm; (△) $T = 331.35$ K isotherm.

method, the apparatus constant can be determined by

$$N = \frac{\rho_{i-1}}{\rho_i} = \sqrt[i]{\rho_0/\rho_i} \tag{2}$$

where ρ_0 is the initial density and ρ_i is the density after the ith expansion. The densities of helium were calculated from an internationally accepted equation of state (Angus et al., 1977) using experimental temperatures on the ITPS-68 scale converted from the ITS-90 scale (Preston-Thomas, 1990) and experimental pressures.

An apparatus constant also can be determined from the pressure ratio (Silberberg et al., 1959) with

$$N = \lim_{P_i \to 0} \frac{P_{i-1}}{P_i} = \lim_{P_{i-1} \to 0} \frac{P_{i-1}}{P_i} \tag{3}$$

where P_i is the pressure after ith expansion. The apparatus constants were extrapolated as 1.32882 and 1.32885 by pressure ratio vs pressure linear extrapolation along $T = 317.65$ K and $T = 331.35$ K isotherms, respectively. The apparatus constant was determined to be

$$N = 1.3288 \pm 0.0001 \tag{4}$$

The experimental densities of helium were calculated from the expansion pressures using $N = 1.3288$. Figure 2 shows the deviations of experimental densities from the values calculated using the equation of state for helium; the maximum deviation is less than 0.02%.

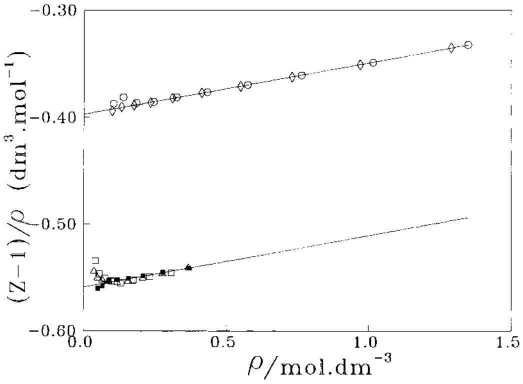

Figure 3. $(Z-1)/\rho$ vs ρ along Burnett isotherms for HFC-227ea. $T = 363.15$ K: (○) isotherm 1; (◇) isotherm 2. $T = 318.15$ K: (□) isotherm 1; (△) isotherm 2; (■) isotherm 3.

Table 1. Burnett Isotherms for HFC-227ea

No.	T (K)	P (kPa)	ρ (mol·dm^{-3})	Z
		363.15 K: Isotherm 1		
0	363.151	2247.066	1.348 9	0.551 70
1	363.149	1980.337	1.015 2	0.646 08
2	363.150	1670.963	0.763 97	0.724 39
3	363.150	1366.938	0.574 93	0.787 43
4	363.152	1093.654	0.432 67	0.837 15
5	363.150	861.107	0.325 61	0.875 87
6	363.150	669.939	0.245 04	0.905 48
7	363.151	517.103	0.184 41	0.928 71
8	363.150	396.858	0.138 78	0.947 10
9	363.151	302.586	0.104 44	0.959 56
		363.15 K: Isotherm 2		
0	363.150	2210.563	1.289 7	0.567 68
1	363.152	1932.807	0.970 55	0.659 56
2	363.151	1621.694	0.730 39	0.735 35
3	363.150	1321.256	0.549 66	0.796 10
4	363.149	1054.108	0.413 65	0.843 97
5	363.149	828.164	0.311 30	0.881 09
6	363.151	643.359	0.234 27	0.909 53
7	363.150	495.850	0.176 30	0.931 48
8	363.150	379.868	0.132 68	0.948 23
9	363.151	289.612	0.099 85	0.960 63
		318.15 K: Isotherm 1		
0	318.150	675.371	0.306 59	0.832 76
1	318.148	533.069	0.230 75	0.873 32
2	318.151	415.339	0.173 67	0.904 07
3	318.152	320.691	0.130 71	0.927 47
4	318.150	246.079	0.098 38	0.945 58
5	318.151	187.885	0.074 05	0.959 23
6	318.149	142.931	0.055 73	0.969 55
7	318.150	108.469	0.041 95	0.977 59
		318.15 K: Isotherm 2		
0	318.151	779.247	0.367 45	0.801 69
1	318.150	621.181	0.276 56	0.849 11
2	318.152	487.634	0.208 15	0.885 62
3	318.149	378.556	0.156 66	0.913 47
4	318.151	291.546	0.117 91	0.934 72
5	318.150	223.237	0.088 75	0.950 94
6	318.151	170.176	0.066 79	0.963 16
7	318.151	129.308	0.050 27	0.972 37
8	318.148	98.031	0.037 83	0.979 45
		318.15 K: Isotherm 3		
0	318.151	781.831	0.369 34	0.800 24
1	318.149	623.810	0.277 92	0.848 53
2	318.150	489.793	0.209 13	0.885 39
3	318.148	380.205	0.157 36	0.913 38
4	318.151	292.761	0.118 41	0.934 66
5	318.150	224.088	0.089 10	0.950 75
6	318.149	170.725	0.067 05	0.962 62
7	318.151	129.685	0.050 45	0.971 76

Results and Analysis

Burnett expansion measurements were made both at 318.15 K and at 363.15 K. Twenty-five pressures were measured in three separate runs totaling twenty-two expansions ranging in density from 0.037 to 0.37 mol·dm^{-3} at 318.15 K, and twenty pressures were measured in two separate runs totaling eighteen expansions ranging in density from 0.10 to 1.3 mol·dm^{-3} at 363.15 K. Results are given in Table 1. The densities of Burnett expansion data were analyzed with a two-coefficient virial equation of state; the density uncertainty was estimated to be within ±1%. In Figure 3, $(Z-1)/\rho$ values calculated from the present data are plotted along Burnett expansion isotherms. As shown in this figure, each isotherm can be represented by a straight line. The second and third virial coefficients of HFC-227ea were determined to be $B = -0.3971$ dm^3·mol^{-1} and $C = 0.04770$ dm^6·mol^{-2} at 363.15 K and $B = -0.5589$ dm^3·mol^{-1} and $C = 0.04802$ dm^6·mol^{-2} at 318.15 K. After the pressure−density relationships were established both at 363.15 K and at 318.15 K, data were collected along nine isochores. Data along eight isochores

Table 2. Isochoric PVT Data for HFC-227ea

T (K)	P (kPa)	ρ (mol·dm^{-3})	ρ_{cal} (mol·dm^{-3})	$100(\rho - \rho_{cal})/\rho_{cal}$
Isochore 1				
363.150	2200.003	1.274 49	1.276 34	−0.145
368.151	2292.837	1.274 17	1.275 24	−0.084
373.150	2383.326	1.273 86	1.273 63	0.018
377.149	2454.858	1.273 60	1.272 84	0.060
Isochore 2				
353.150	1791.435	0.959 73	0.959 01	0.074
358.151	1856.744	0.959 49	0.959 27	0.023
363.152	1920.530	0.959 25	0.959 10	0.016
368.150	1983.009	0.959 01	0.958 66	0.037
373.149	2044.366	0.958 77	0.958 08	0.073
377.150	2092.981	0.958 58	0.957 73	0.088
Isochore 3				
343.150	1421.929	0.714 91	0.714 47	0.061
348.151	1467.092	0.714 73	0.714 58	0.020
353.150	1511.332	0.714 55	0.714 53	0.003
358.152	1554.817	0.714 37	0.714 39	−0.003
363.149	1597.538	0.714 20	0.714 13	0.009
368.150	1639.779	0.714 02	0.713 89	0.018
373.148	1681.393	0.713 84	0.713 56	0.039
377.150	1714.508	0.713 70	0.713 39	0.044
Isochore 4				
333.150	1093.805	0.523 48	0.523 41	0.014
338.151	1124.531	0.523 35	0.523 37	−0.003
343.150	1154.633	0.523 22	0.523 23	−0.001
348.148	1184.371	0.523 09	0.523 13	−0.006
353.149	1213.635	0.522 96	0.522 96	0.001
358.150	1242.654	0.522 83	0.522 84	−0.001
363.151	1271.268	0.522 70	0.522 66	0.009
368.150	1299.643	0.522 57	0.522 49	0.017
373.152	1327.748	0.522 44	0.522 30	0.027
377.150	1350.015	0.522 34	0.522 13	0.041
Isochore 5				
323.150	841.024	0.392 87	0.392 74	0.033
328.151	862.735	0.392 77	0.392 60	0.043
333.150	884.212	0.392 68	0.39252	0.039
338.151	905.527	0.392 58	0.392 51	0.017
343.149	926.604	0.392 48	0.392 50	−0.004
348.148	947.326	0.392 38	0.392 41	−0.007
353.150	967.799	0.392 29	0.392 30	−0.004
358.151	988.147	0.392 19	0.392 21	−0.006
363.151	1008.299	0.392 09	0.392 10	−0.004
368.151	1028.270	0.391 99	0.391 98	0.004
373.150	1048.133	0.391 90	0.391 86	0.009
377.149	1063.835	0.391 82	0.391 72	0.024
Isochore 6				
313.151	625.442	0.28706	0.28709	−0.011
318.150	640.538	0.28699	0.28701	−0.007
323.149	655.403	0.28692	0.28691	0.003
328.151	670.249	0.28685	0.28689	−0.016
333.151	684.828	0.28678	0.28682	−0.016
338.149	699.247	0.28671	0.28674	−0.013
343.151	713.565	0.28663	0.28668	−0.015
348.150	727.721	0.28656	0.28659	−0.009
353.151	741.783	0.28649	0.28651	−0.005
358.150	755.820	0.28642	0.28645	−0.010
363.151	769.627	0.28635	0.28633	0.007
368.150	783.428	0.28628	0.28624	0.014
373.149	797.201	0.28621	0.28617	0.015
377.151	808.119	0.28615	0.28608	0.023
Isochore 7				
303.151	496.934	0.230 24	0.230 26	−0.011
308.151	508.812	0.230 18	0.230 24	−0.027
313.149	520.534	0.230 12	0.230 20	−0.035
318.150	532.086	0.230 06	0.230 14	−0.033
323.150	543.554	0.230 01	0.230 09	−0.039
328.150	554.947	0.229 95	0.230 07	−0.052
333.150	566.146	0.229 89	0.230 00	−0.046
338.151	577.310	0.229 84	0.229 95	−0.051
343.150	588.366	0.229 78	0.229 90	−0.051
348.151	599.298	0.229 72	0.229 82	−0.042
353.150	609.956	0.229 66	0.229 65	0.006
358.149	620.731	0.229 61	0.229 56	0.021

Table 2 (Continued)

T (K)	P (kPa)	ρ (mol·dm^{-3})	ρ_{cal} (mol·dm^{-3})	$100(\rho - \rho_{cal})/\rho_{cal}$
		Isochore 7		
363.150	631.660	0.229 55	0.229 55	0.000
368.151	642.441	0.229 49	0.229 50	−0.004
373.151	653.186	0.229 44	0.229 45	−0.008
377.150	661.707	0.229 39	0.229 40	−0.004
		Isochore 8		
293.152	351.041	0.162 02	0.162 04	−0.014
298.150	358.854	0.161 98	0.161 96	0.010
303.148	366.689	0.161 94	0.161 92	0.013
308.151	374.380	0.161 90	0.161 83	0.040
313.150	382.257	0.161 86	0.161 87	−0.004
318.151	389.757	0.161 82	0.161 75	0.044
323.151	397.490	0.161 78	0.161 77	0.008
328.150	405.004	0.161 74	0.161 71	0.019
333.148	412.462	0.161 70	0.161 65	0.032
338.149	419.970	0.161 66	0.161 63	0.020
343.151	427.571	0.16162	0.161 66	−0.026
348.151	434.879	0.161 58	0.161 59	−0.005
353.150	442.235	0.161 54	0.161 55	−0.005
358.150	449.542	0.161 50	0.161 50	0.001
363.151	456.870	0.161 46	0.161 47	−0.005
368.150	464.114	0.161 42	0.161 41	0.004
373.151	471.388	0.161 38	0.161 38	0.000
377.150	477.143	0.161 35	0.161 33	0.009
		Isochore 9		
283.151	265.102	0.124 22	0.124 19	0.024
288.150	270.983	0.124 19	0.124 19	−0.001
293.149	276.873	0.124 16	0.124 19	−0.027
298.151	282.738	0.124 13	0.124 19	−0.047
303.151	288.284	0.124 10	0.124 05	0.044
308.151	294.173	0.124 07	0.124 08	−0.007
313.150	299.952	0.124 04	0.124 07	−0.029
318.150	305.508	0.124 01	0.123 99	0.016

Table 3. Comparison of Burnett Isotherms Using Isochoric Coupling

isochore	P_{318} (kPa)	ρ_{318} (mol·dm^{-3})	ρ_{363} (mol·dm^{-3})	ρ_{EOS} (mol·dm^{-3})	$100((\rho_{318} - \rho_{363})/\rho_{363})$	$100((\rho_{318} - \rho_{EOS})/\rho_{EOS})$
6	640.538	0.280 77	0.286 99	0.287 01	0.028	0.021
7	532.086	0.230 17	0.230 06	0.230 14	0.048	0.013
8	389.757	0.161 76	0.161 82	0.161 75	−0.037	0.006

were measured in the temperature range from 293.15 to 377.15 K; the pressure measurement for each isochore at 363.15 K was used to determine the density. Data along one other isochore were measured in the temperature range from 283.15 to 318.15 K; the pressure measurement for the isochore at 318.15 K was used to determine the density. A temperature correction to the densities was made to compensate for the thermal expansion of the sample cell. Results of the isochoric measurements are given in Table 2. Figure 4 shows the location in pressure and temperature of the present data and of the vapor pressure data of Shi et al. (1999).

The densities of isochores 6−8 are also calculated from the 318.15 K isotherm to examine the experimental accuracy. Table 3 contains the densities determined by a different method. The densities ρ_{363} listed in Table 3 were calculated using the isochore pressures at 363.15 K and then corrected for volume distortion due to thermal expansion as temperature changes to provide the densities at 318.15 K; the densities labeled ρ_{318} come from the isochore pressures at 318.15 K and the densities ρ_{EOS} were calculated from the equation of state. The maximum difference of ρ_{363} and ρ_{318} was less than 0.1%.

Equation of State

The present data and the results of Pátek et al. (1998) having densities less than 2.5 mol·dm^{-3} were correlated with a virial equation including temperature dependence,

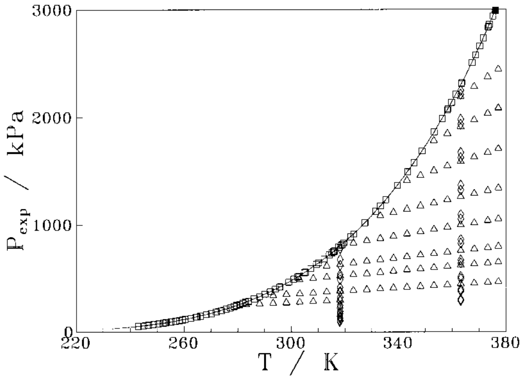

Figure 4. Distribution of PVT and vapor pressure measurements for HFC-227ea. (□) Vapor pressure data (Shi et al., 1999); (—) calculation from vapor pressure equation (Shi et al., 1999); (■) critical point; (◇) Burnett measurements; (△) isochoric measurements.

$$\frac{P}{\rho RT} = 1 + B\rho + C\rho^2 + D\rho^3 \tag{5}$$

where

$$B = B_0 + B_1 T_r^{-1} + B_2 T_r^{-2} + B_3 T_r^{-3} + B_4 T_r^{-6} + B_5 T_r^{-8}$$

$$C = C_0 T_r^{-5} + C_1 T_r^{-6}$$

$$D = D_0 + D_1 T_r$$

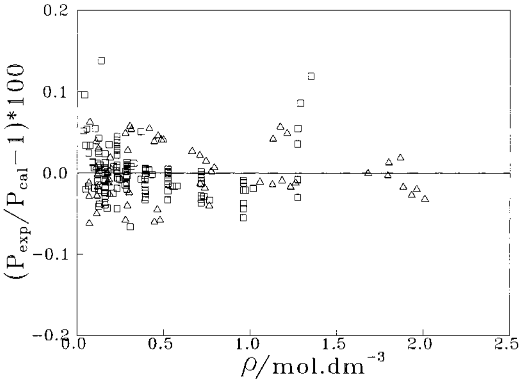

Figure 5. Pressure deviations of measured PVT data for HFC-227ea from values calculated using eq 5: (□) this work; (△) Pátek et al. (1998).

and

$$B_0 = -11.149\ 851\ 83\ \mathrm{dm^3{\cdot}mol^{-1}}$$

$$B_1 = 43.231\ 998\ 03\ \mathrm{dm^3{\cdot}mol^{-1}}$$

$$B_2 = -59.124\ 655\ 41\ \mathrm{dm^3{\cdot}mol^{-1}}$$

$$B_3 = -29.006\ 193\ 43\ \mathrm{dm^3{\cdot}mol^{-1}}$$

$$B_4 = -2.824\ 121\ 515\ \mathrm{dm^3{\cdot}mol^{-1}}$$

$$B_5 = 0.497\ 630\ 556\ 3\ \mathrm{dm^3{\cdot}mol^{-1}}$$

$$C_0 = 0.181\ 900\ 845\ 4\ \mathrm{dm^6{\cdot}mol^{-2}}$$

$$C_1 = -0.135\ 926\ 448\ 8\ \mathrm{dm^6{\cdot}mol^{-2}}$$

$$D_0 = -8.889\ 623\ 857 \times 10^{-3}\ \mathrm{dm^9{\cdot}mol^{-3}}$$

$$D_1 = -8.353\ 339\ 687 \times 10^{-3}\ \mathrm{dm^9{\cdot}mol^{-3}}$$

$$R = 8.314471\ \mathrm{J{\cdot}mol^{-1}{\cdot}K^{-1}}$$

$$T_r = T/T_c$$

$$T_c = 375.95\ \mathrm{K}$$

and where the units of T are K, those of P are kPa, and those of ρ are mol·dm^{-3}.

The suitable range of this equation is from 283 to 453 K in temperature and up to 2.5 mol·dm^{-3} in density. The maximum and root mean square pressure deviations of our data from eq 5 were 0.14% and 0.030%, respectively, and 0.064% and 0.034% for the results of Pátek et al. (1998). Figures 5 and 6 show the pressure and density deviations of our data and the results of Pátek et al. (1998) from eq 5. Figure 7 shows the pressure deviations of the values of Park (1993) having densities less than 2.5 mol·dm^{-3} from eq 5; Park's values are 0.05% to 1.3% higher than eq 5. The critical temperature (T_c) needed in this equation comes from Defibaugh and Moldover (1997).

Conclusions

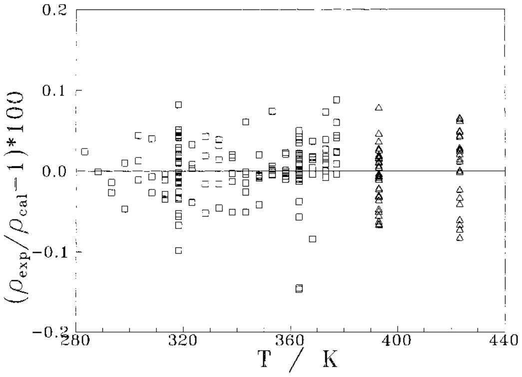

Figure 6. Density deviations of measured PVT data for HFC-227ea from values calculated using eq 5 (one point out of the scale); (□) this work; (△) Pátek et al. (1998).

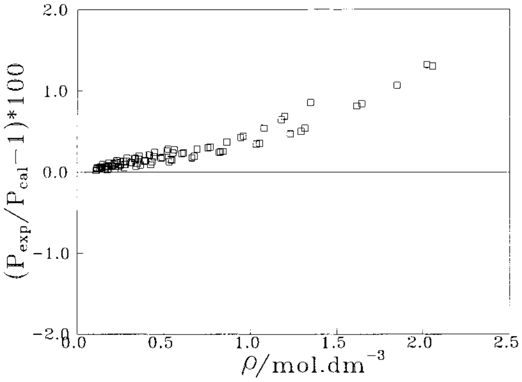

Figure 7. Pressure deviations of Park's results for HFC-227ea from values calculatedd using eq 5: (□) Park (1993).

Some 141 PVT data points for HFC-227ea in the gaseous phase have been measured using Burnett/isochoric methods. The temperature range is from 283 to 377 K, the pressure range is from 0.1 to 2.5 MPa, and the density range is from 0.037 to 1.35 mol·dm^{-3}. The maximum temperature uncertainty and maximum pressure uncertainty in this work were estimated to be within ±10 mK and ±500 Pa, respectively. The parameters of a virial equation of state were determined to represent the gaseous thermodynamic properties of HFC-227ea.

Acknowledgment

We thank D. R. Defibaugh and J. Pátek for providing the experimental data for the vapor pressure and PVT properties of HFC-227ea. We also thank Mr. Yi-Dong Fu for providing useful help in the measurements. This work is supported by the National Nature Science Foundation of China (Grant No. 59906006) and part of this work is supported by the Department of Thermal Engineering, Tsinghua University.

Literature Cited

Angus, S.; de Reuck, K. M.; McCarty, R. D. *International Thermodynamic Tables of the Fluid State Helium-4*, Pergamon: Oxford, 1977.

Defibaugh, D. R.; Moldover, M. R. Compressed and Saturated Liquid Densities for 18 Halogenated Organic Compounds. *J. Chem. Eng. Data* **1997**, *42*, 650−652.

Duan, Y. Y.; Zhu, M. S.; Han, L. Z. Experimental Pressure−Volume−Temperature Data and An Equation of State for Trifluoroiodomethane (CF$_3$I) in Gaseous Phase. *Fluid Phase Equilibr.* **1997**, *131*, 233−241.

Fu, Y. D.; Han, L. Z.; Zhu, M. S. PVT Properties, Vapor Pressures and Critical Parameters of HFC-32. *Fluid Phase Equilibr.* **1995**, *111*, 273−286.

Huber, M.; Gallagher, J.; Mclinden, M.; Morrison G. NIST Standard Reference Database 23: NIST Thermodynamic properties of refrigerants and refrigerant mixtures database (RETPROP), version 5.0. U. S. Department of Commerce Washington, DC, 1996.

Klomfar, J.; Hruby, J.; Sifner, O. Measurements of the (T, P, ρ) Behaviour of 1,1,1,2,3,3,3-Heptafluoropropane (Refrigerant R227) in the Liquid Phase. *J. Chem. Thermodyn.* **1994**, *26*, 965−970.

Laesecke, A.; Hafer, R. F. Viscosity of Fluorinated Propane Isomers. 2. Measurements of Three Compounds and Model Comparisons. *J. Chem. Eng. Data* **1998**, *43*, 84−92.

Liu, X. Y.; Shi, L.; Zhu, M. S.; Han, L. Z. Liquid Viscosity of 1,1,1,2,3,3,3-Heptafluoropropane (HFC-227ea) along the Saturation Line. *J. Chem. Eng. Data* **1999a**, *44*, 688−692.

Liu, X. Y.; Shi, L.; Duan, Y. Y.; Zhu, M. S.; Han, L. Z. Thermal Conductivity of Gaseous 1,1,1,2,3,3,3-Heptafluoropropane (HFC-227ea). *J. Chem. Eng. Data.* **1999b**, *44*, 882−886.

Park, Y. J. Bestimmung des thermischen Verhaltens neuer Arbeitsstoffe der Energietechnik mit Hife einer Burnett-Apparatus. Thesis, Universitat Karlsruhe, 1993.

Pátek, J.; Klomfar, J.; Prazak, J.; Sifner, O. The (P, ρ, T) Behaviour of 1,1,1,2,3,3,3-Heptafluoropropane (HFC-227ea) Measured with a Burnett Apparatus. *J. Chem. Thermodyn.* **1998**, *30*, 1159−1172.

Preston-Thomas, H. The International Temperature Scale of 1990 (ITS-90). *Metrologia* **1990**, *27*, 3−10.

Robin, M. L. Thermophysical Properties of HFC-227ea. *Proceedings of 1994 International CFC & Halon Alternatives Conference* Washington, DC; 1994; pp 105−113.

Salvi-Narkhede, M.; Wang, B. H.; Adcock, J. L.; Van Hook, W. A. Vapor Pressures, Liquid Molar Volumes, Vapor Nonideality, and Critical Properties of some Partially Fluorinated Ethers ($CF_3OCF_2CF_2H$, CF_3OCF_2H, and CF_3OCH_3), Some Perfluoroethers ($CF_3OCF_2OCF_3$, *c*-$CF_2OCF_2OCF_2$, and *c*-$CF_2CF_2CF_2O$) and of CHF_2Br and CF_3-$CFHCF_3$. *J. Chem. Thermodyn.* **1992**, *24*, 1065−1075.

Shi, L.; Duan, Y. Y.; Zhu, M. S.; Han, L. Z.; Lei, X. Vapor Pressure of 1,1,1,2,3,3,3-Heptafluoropropane. *Fluid Phase Equilibr.* **1999**, *163*, 109−117.

Silberberg, I. A.; Kobe, K. A.; McKetta, J. J. Gas Compressibilities with the Burnett Apparatus, Method and Apparatus. *J. Chem. Eng. Data* **1959**, *4*, 314−323.

Weber, L. A. Personal communication, 1998.

Wirbser, H.; Bräuning, G.; Gurtner, J.; Ernst, G. Flow-Calorimetric Specific Heat Capacities and Joule-Thomson Coefficients of CF_3-$CFHCF_3$ (R227) −a New Working Fluid in Energy Technics−at Pressures up to 15MPa and Temperatures Between 253K and 423K. *J. Chem. Thermodyn.* **1992**, *24*, 761−772.

Zhu, M. S.; Fu, Y. D.; Han, L. Z. An Experimental Study of PVT Properties of CFC Alternative HFC-134a. *Fluid Phase Equilibr.* **1992**, *80*, 149−156.

Received for review May 14, 1999. Accepted September 3, 1999.

JE9901334