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Viscosity of Gaseous HFC-125 (Pentafluoroethane) Under High Pressures

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This paper reports experimental results for the viscosity of gaseous HFC-125 (pentafluoroethane) under high pressures. The measurements were carried out with an oscillating-disk viscometer of the Maxwell type at temperatures from 298.15 to 423.15 K and at pressures up to the saturated vapor pressures at each temperature at subcritical conditions or up to 9 MPa at supercritical temperatures. Intermolecular scaling parameters of HFC-125 for the extended corresponding states were determined from the viscosity data at 0.1 MPa. An empirical viscosity equation is proposed to interpolate the present experimental results as a function of temperature and density.

KEY WORDS: corresponding states; HFC-125; oscillating-disk viscometer; viscosity.

1. INTRODUCTION

As part of our continuing experimental program for measuring the viscosity of gaseous alternative refrigerants, we previously reported experimental results for HFC-32 [1], HFC-134a [2], and HFC-143a [3]. In this paper, we report experimental results for the viscosity of gaseous HFC-125 (pentafluoroethane) under high pressures. HFC-125 is considered as a substitute for HCFC-22 and is a constituent in the alternative refrigerant mixtures HFC-507, HFC-410A, HFC-404A, and HFC-407C.

The measurements were made with an oscillating-disk viscometer of the Maxwell type at temperatures from 298.15 to 423.15 K and at pressures

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up to the saturated vapor pressures at subcritical temperatures or up to 9 MPa at supercritical temperatures. The viscosity data at 0.1 MPa were used to determine the scaling parameters of HFC-125 for the extended law of corresponding states. The data at high pressures were used to develop an empirical viscosity equation as a function of temperature and density.

The viscosity of HFC-125 in the liquid phase has been measured by Diller and Peterson [4] and by Oliveira and Wakeham [5]. The viscosity of HFC-125 in the gaseous phase at 298.15 K and at 0.1 MPa has been measured by Dunlop [6]. The gaseous viscosity of HFC-125 under high pressures, however, has not yet been reported.

2. EXPERIMENTS

The viscosity was measured with an oscillating-disk viscometer of the Maxwell type. The gas density under the experimental conditions of the viscosity measurement was determined with a high-pressure gas pipette. The experimental apparatus and procedures were the same as those described in previous studies [7–10]. The apparatus constant of the viscometer at the experimental temperatures and pressures was determined by considering the viscosity data of nitrogen taken from Stephan et al. [11] and the nitrogen-gas density data from Jacobsen et al. [12]. Temperature and pressure values have an uncertainty of 0.01 K and 0.5 kPa, respectively. Density values have an uncertainty of 0.03 $\text{kg} \cdot \text{m}^{-3}$. The estimated error in the viscosity measurements is within 0.3%.

The sample was supplied by Asahi Glass Co.Ltd. The purity of the sample, as certified by the suppliers, was approximately 99.9 mol%. The sample was purified by distillation several times.

3. RESULTS

The experimental results for viscosity and density are presented in Table I and shown in Figs. 1 and 2. For the viscosity at 298.15 K and 0.1 MPa, the present result is about 0.23% higher than the viscosity value of Dunlop [6].

The low-pressure gas viscosity can be represented by the Chapman–Enskog equation derived from the kinetic theory for dilute gases:

$$\eta_0 = \frac{5}{16} \frac{(MkT)^{0.5}}{(\pi N)^{0.5}} \frac{f_\eta}{\sigma^2 \Omega^{(2,2)*}(T^*)} \tag{1}$$

In Eq. (1), k is Boltzmann's constant, M is the molar mass in $\text{kg} \cdot \text{kmol}^{-1}$, N is Avogadro's number, $\Omega^{(2,2)*}(T^*)$ is the collision integral, f_η is the

Table I. Viscosity of HFC-125

P (MPa)	ρ ($kg \cdot m^{-3}$)	η ($\mu Pa \cdot s$)
	$T = 298.15$ K	
0.1015	4.994	12.971
0.2469	12.444	12.985
0.3919	20.260	13.002
0.5382	28.603	13.013
0.6888	37.742	13.030
0.8367	47.370	13.097
0.9794	57.395	13.142
1.1225	68.345	13.238
1.2315	77.447	13.299
1.3278	86.157	13.389
	$T = 323.15$ K	
0.1021	4.617	14.006
0.2468	11.356	14.004
0.3923	18.392	14.038
0.5385	25.741	14.080
0.6864	33.489	14.108
0.8362	41.717	14.140
0.9796	49.974	14.188
1.1276	58.945	14.270
1.3222	71.546	14.382
1.4220	78.421	14.450
1.5686	89.119	14.603
1.7170	100.80	14.763
1.8615	113.18	14.970
2.0040	126.62	15.167
2.1271	139.47	15.419
2.2158	149.65	15.600
2.2737	156.81	15.719
	$T = 348.15$ K	
0.1016	4.249	15.032
0.3577	15.329	15.036
0.6248	27.496	15.116
0.8662	39.094	15.214
1.1266	52.348	15.317
1.3882	66.434	15.479
1.6574	82.240	15.656
1.9076	98.011	15.888
2.2059	118.63	16.223
2.4408	136.60	16.608
2.6325	152.68	16.921
2.8464	172.51	17.341
3.0404	192.69	17.873
3.2306	215.14	18.424
3.4453	244.91	19.370

Table I. *(Continued)*

P (MPa)	ρ (kg · m^{-3})	η (μPa · s)
3.5644	264.26	19.940
3.6775	285.23	20.669
3.7743	305.89	21.382
3.8678	329.06	22.322
3.9294	346.63	23.094
3.9992	369.49	24.123
4.0587	392.18	25.248
4.1065	413.18	26.248
4.1660	443.51	28.061
4.2153	472.68	29.895
4.2568	499.88	31.638
4.2938	525.63	33.517
4.3307	551.67	35.297
4.3606	572.35	36.993
	$T = 373.15$ K	
0.1018	3.965	16.019
0.3919	15.595	16.086
0.6914	28.142	16.176
0.9967	41.565	16.287
1.3147	56.301	16.443
1.6328	71.907	16.648
1.9489	88.393	16.874
2.2877	107.30	17.204
2.5867	125.22	17.545
2.8294	140.73	17.863
3.1615	163.60	18.373
3.4540	185.56	18.951
3.7208	207.34	19.528
3.9662	229.11	20.131
4.2486	256.55	21.024
4.4806	281.30	21.826
4.5762	292.16	22.307
4.6169	296.89	22.399
4.6552	301.43	22.555
4.8836	329.89	23.760
5.0585	353.44	24.707
5.3354	393.90	26.859
5.4849	417.25	27.708
5.6413	442.65	29.031
5.7999	469.12	30.492
5.9489	494.32	31.898
	$T = 398.15$ K	
0.1022	3.727	17.001
0.3370	12.453	17.016
0.5986	22.459	17.118

Table I. *(Continued)*

P (MPa)	ρ (kg · m^{-3})	η (μPa · s)
0.8651	32.982	17.226
1.2281	47.886	17.356
1.3716	53.969	17.465
1.8919	77.027	17.782
2.3221	97.393	18.090
2.7084	116.80	18.445
3.1258	139.08	18.918
3.5321	162.24	19.460
3.9239	186.07	20.115
4.3026	210.64	20.763
4.6189	232.40	21.476
4.9377	255.55	22.172
5.2395	278.63	22.981
5.4538	295.72	23.586
5.6320	310.37	24.153
5.7985	324.42	24.774
5.8858	331.91	25.033
6.0872	349.54	25.764
6.3298	371.37	26.739
6.5616	392.74	27.737
6.7249	408.07	28.508
	$T = 423.15$ K	
0.1015	3.4800	17.954
0.4236	14.733	18.006
0.7468	26.364	18.101
1.0731	38.478	18.218
1.4617	53.407	18.440
1.8607	69.344	18.623
2.2757	86.611	18.935
2.6862	104.42	19.242
3.1093	123.58	19.625
3.4858	141.58	20.023
3.8596	159.70	20.510
4.2965	182.04	21.034
4.6992	203.52	21.630
5.0497	222.91	22.238
5.3798	241.76	22.813
5.7162	261.54	23.514
6.0856	283.92	24.338
6.4272	305.18	25.161
6.7334	324.64	25.862
7.0630	346.00	26.748
7.3354	363.91	27.564
7.6183	382.70	28.398
7.9156	402.60	29.335
8.1485	418.24	30.148
8.3978	434.99	30.980

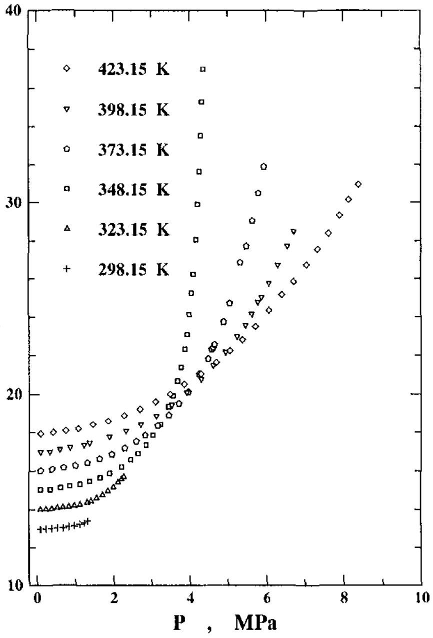

Fig. 1. Viscosity of HFC-125 as a function of pressure.

higher-order correction factor for viscosity, $T^* = kT/\varepsilon$ is the reduced temperature, T is the absolute temperature, η_0 is the gas viscosity at 0.1 MPa in μPa · s, and ε and σ are the characteristic scaling parameters. As for the collision integral and correction factor, we have used the equations proposed by Kestin et al. [13] in developing the extended corresponding states. The values of the scaling parameters, ε and σ, were determined by a least-squares fit of Eq. (1) to the gas viscosity data at 0.1 MPa. The optimum values of the parameters, ε and σ, are given in Table II. The deviations between the experimental viscosities and the values calculated from Eq. (1) are shown in Fig. 3. The present viscosity data can be represented well by Eq. (1) with the values of the scaling parameters in Table II, with a maximum deviation of 0.07% and an average deviation of 0.03%.

For the gas viscosity η at temperature T and at high pressures, we developed the following empirical viscosity equation as a function of temperature and density:

$$\eta = \eta_0 + a_0(\rho - \rho_0) + a_1(\rho - \rho_0)^2 + a_2(\rho - \rho_0)^3 \qquad (2)$$

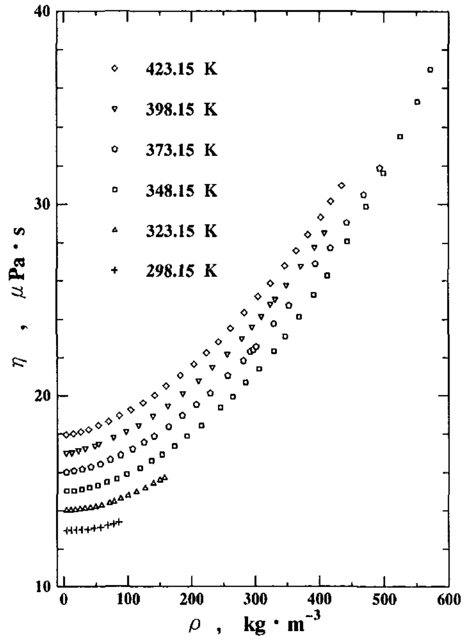

Fig. 2. Viscosity of HFC-125 as a function of density.

with

$$a_0 = -3.441313 \times 10^{-5} T + 4.064119 \times 10^{-2} - 8.201175/T \tag{3}$$

$$a_1 = -7.085351 \times 10^{-7} T + 6.803836 \times 10^{-4} - 1.346352 \times 10^{-1}/T \tag{4}$$

$$a_2 = 2.234668 \times 10^{-9} T - 1.92707 \times 10^{-6} + 4.073205 \times 10^{-4}/T \tag{5}$$

where η_0 is the gas viscosity at 0.1 MPa represented by Eq. (1), ρ is the gas density at high pressures in kg · m^{-3}, ρ_0 is the gas density at 0.1 MPa in

Table II. Scaling Parameters for HFC-125 and Deviations of Experimental Viscosity at 0.1 MPa from Eq. (1)[a]

ε/k	235.85 K
σ	0.5260 nm
Average deviation	0.03 %
Maximum deviation	0.07 %

[a] Average deviation = 100 $|\eta_{0,\,\mathrm{EXP}} - \eta_{0,\,\mathrm{CAL}}|/\eta_{0,\,\mathrm{CAL}}/n$. Maximum deviation = max of 100 $|\eta_{0,\,\mathrm{EXP}} - \eta_{0,\,\mathrm{CAL}}|/\eta_{0,\,\mathrm{CAL}}$. n = number of data.

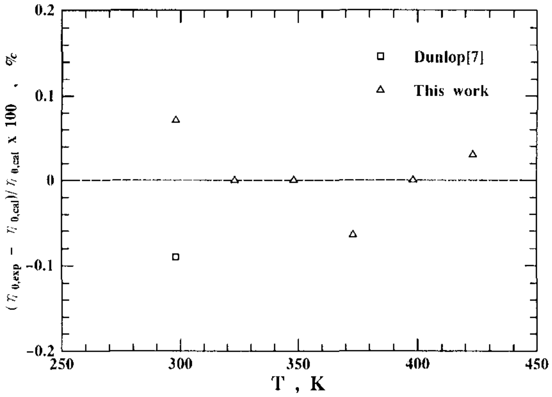

Fig. 3. Deviations of experimental viscosity values of HFC-125 at 0.1 MPa from those calculated with Eq. (1).

kg · m^{-3}, and T is the absolute temperature in K. The values of the coefficients in Eqs. (3) and (4) were determined from a least-squares fit of Eq. (2) to the present experimental viscosity values. Figure 4 shows the deviations of the present results from Eq. (2). As can be seen from Fig. 4, Eq. (2) represents the present results with an average deviation of 0.16% and a maximum deviation of 1.0%. Note that Eq. (2) should be used only within the temperature and density ranges of this study.

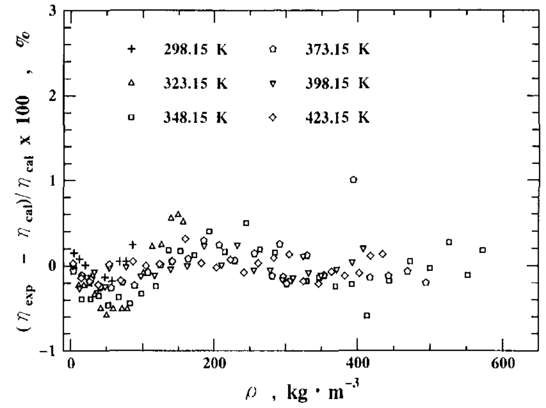

Fig. 4. Deviations of experimental viscosity values of HFC-125 under high pressures from those calculated with Eq. (2).

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