

Viscosity of Gaseous HFC245fa

Xiaopo Wang, Jiangtao Wu,* and Zhigang Liu

State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, People's Republic of China

The viscosity of gaseous HFC245fa (1,1,1,3,3-pentafluoropropane) was measured at the temperature range from (300 to 396) K and pressures up to 1.6 MPa. The measurements were carried out in an oscillating disk viscometer of the Maxwell type, and the measurements were relative to the viscosity of nitrogen. The uncertainty of the reported viscosities was estimated to be within $\pm 2.0\%$ with a coverage factor of $k = 2$. The measured data were correlated as a function of temperature and density with a maximum deviation of 0.53% and an absolute average deviation of 0.21%.

Introduction

HFC245fa (1,1,1,3,3-pentafluoropropane) is currently considered as a promising replacement for chlorine-containing compounds, such as 1,1-dichloro-1-fluoroethane (HCFC-141b) and 1,2-dichloro-1,1,2,2-tetrafluoroethane (CFC-114) for high-temperature heat pumps and chemical blowing agents.¹ For these applications, its thermophysical properties are very important. The vapor pressure,^{2–4} liquid viscosity,⁵ thermal conductivity,⁶ and compressed and saturated liquid densities⁷ have been reported in the literature. To the author's knowledge, only a few experimental viscosity data of gaseous HFC245fa were reported by Geller et al.⁸ using the capillary tube method. In this work, the viscosities of gaseous HFC245fa at temperatures from (300 to 396) K and at pressures up to 1.6 MPa were measured.

Measurement Method and Equipment

The experimental apparatus employed in this work was an oscillating disk viscometer of the Maxwell type⁹ which has been proved to be a reliable instrument to measure the viscosity of gases. The evaluation of the experiments was based on the relative method developed by Kestin et al.^{10,11}

Working Equations. According to Kestin et al., the following working formula for calibrating and evaluating present measurements was used

$$2\theta(\Delta\theta - \Delta_0) = \frac{\pi\rho R^4\delta}{I} C \left\{ H_1 K_2 + H_2 K_1 + \frac{2d}{R} \left[H_1 + \frac{3\delta\theta}{2R} + \frac{3\delta^2\theta}{16R^2x} \right] \right\} \quad (1)$$

where δ is the boundary layer thickness; I is the moment of inertia of the suspension system; C is the edge-correction factor from calibration as a function of boundary layer thickness; ρ is the gaseous density of fluids; Δ and Δ_0 are the logarithmic decrements of damping; and T and T_0 are the periods of oscillation in fluids and in vacuum, respectively. The values of I , d , and R were given in Table 1.

The remaining symbols have the following meanings

* Corresponding author. E-mail: jtwu@mail.xjtu.edu.cn. Fax: 86-29-82668789.

$$H_1 = \frac{3x}{2\theta} - \frac{1}{8x^3\theta^3} \quad (2)$$

$$H_2 = \frac{3}{4x\theta^2} - x^3 \quad (3)$$

$$K_1 = \frac{\sin Y}{\cosh X - \cos Y} \quad (4)$$

$$K_2 = \frac{\sinh X}{\cosh X - \cos Y} \quad (5)$$

$$X = 2\beta x \quad (6)$$

$$Y = \frac{\beta}{x\theta} \quad (7)$$

$$x = \left\{ \frac{\theta}{2} [(\Delta^2 + 1)^{1/2} - \Delta] \right\}^{1/2} \quad (8)$$

$$\theta = T_0/T \quad (9)$$

Before measurement of viscosity of a specified fluid, it was necessary to calibrate the viscometer with a well-known viscosity gas to obtain the edge-correction factor C , and then the boundary layer thickness δ can be obtained via eq 1. Finally, the viscosity is given by

$$\eta = 2\pi\delta^2\rho/T_0 \quad (10)$$

Apparatus. In this work, an oscillating disk viscometer developed by our group¹² was used to measure the gaseous viscosity of HFC245fa. The experimental apparatus and procedure were essentially the same as those described in previous studies.^{13,14} Only a brief description of the apparatus is given here. The schematic diagram of the oscillating disk viscometer is shown in Figure 1.

Table 1. Characteristics of the Suspension System

radius of disk (R /mm)	35.00
thickness of disk (d /mm)	1.12
total separation between the fixed plates (D /mm)	7.98
upper separation (β_1 /mm)	3.43
lower separation (β_2 /mm)	3.43
length of the suspension wire (L /mm)	23.00
diameter of the suspension wire (d_w /mm)	0.05
moment of inertia of the suspension system (I /g·cm ²)	58.5347
period of oscillation at 20 °C in vacuum (T_0 /s)	27.746
the logarithmic decrement at 20 °C in vacuum Δ_0	0.00005

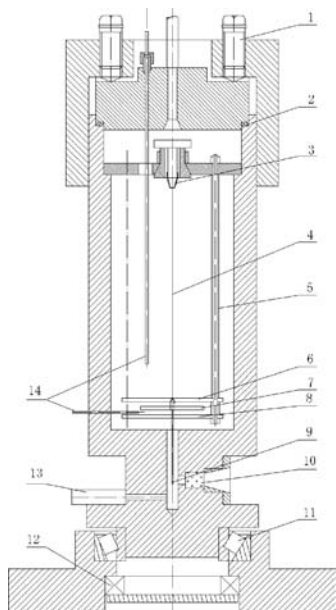


Figure 1. Schematic diagram of the oscillating disk viscometer.¹¹ 1, Bolt; 2, Seal; 3, Clamp; 4, Suspension wire; 5, Quartz tube; 6, Upper fixed disk; 7, Oscillating disk; 8, Lower fixed disk; 9, Mirror; 10, Window; 11, Roller bearing; 12, Ball bearing; 13, Gas inlet; 14, Platinum resistance thermometer.

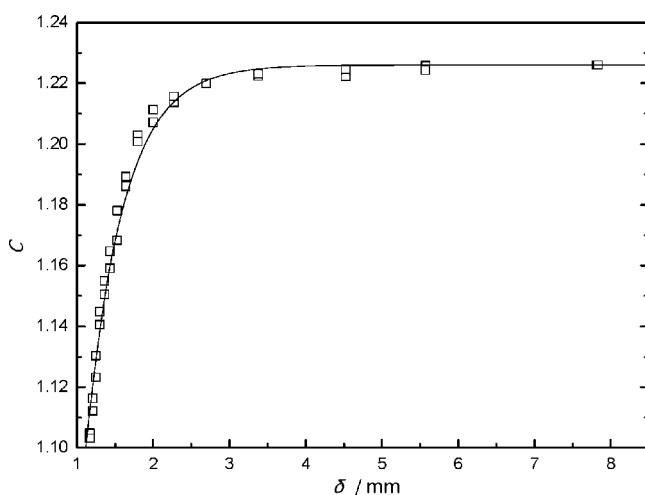


Figure 2. Relation between the edge-correction factor C and boundary layer thickness δ .

The main part of the apparatus is the suspension system, which is composed of an oscillating quartz disk, a suspension wire (92Pt8W, supplied by Goodfellow Cambridge Limited, UK), two fixed stainless steel plates, and a stainless steel stem with a glass mirror. To eliminate the stress of the platinum-tungsten wire, it was heat treated before the experiment. In the suspension system, the distance between the oscillating disk and the upper fixed plate should be equal to the distance between the oscillating disk and the lower fixed plate at any ambient temperatures. To satisfy this requirement, three quartz tubes were inserted between the upper fixed plate and a fixing disk, and three stainless steel spacers were inserted between the two fixed plates. The three quartz tubes and the three spacers were fixed by using three stainless steel rods, nuts, and springs. The characteristics of the suspension system are shown in Table 1.

The temperature of the fluid was established by two controllable heaters and was measured with a platinum-resistance thermometer inside the viscometer positioned in the middle of

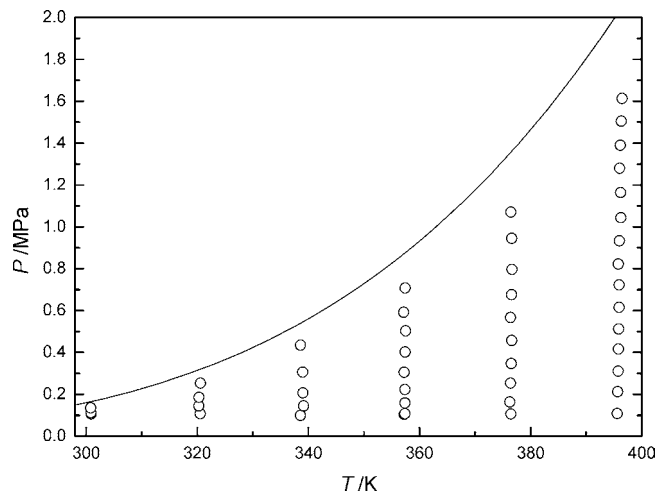


Figure 3. Temperature and pressure ranges for the experimental points: \circ , measured state point; $-$, saturated vapor pressure.

Table 2. Viscosity of Argon

T K	P MPa	ρ $\text{kg}\cdot\text{m}^{-3}$	$\eta/\mu\text{Pa}\cdot\text{s}$		$100(\eta_{\text{exp}} - \eta_{\text{ref}})/\eta_{\text{ref}}$
			η_{exp}	η_{ref}^{16}	
300.58	4.503	73.758	23.833	23.744	0.372
300.56	4.050	66.187	23.640	23.622	0.078
300.70	3.729	60.824	23.510	23.547	-0.160
300.63	3.427	55.827	23.433	23.468	-0.148
300.54	3.089	50.255	23.473	23.380	0.396
300.66	2.759	44.784	23.385	23.310	0.323
300.72	2.458	39.822	23.376	23.246	0.561
300.49	2.082	33.698	23.351	23.149	0.871
300.76	1.775	28.641	23.247	23.101	0.631
300.68	1.446	23.308	23.126	23.030	0.418
300.89	1.117	17.948	22.932	22.979	-0.204
300.32	0.832	13.375	22.861	22.889	-0.123
300.38	0.616	9.882	22.801	22.854	-0.235
300.11	0.400	6.426	22.715	22.799	-0.370
300.25	0.302	4.838	22.651	22.791	-0.615
300.19	0.199	3.196	22.646	22.770	-0.545
300.17	0.103	1.643	22.788	22.752	0.157

the fixed plates. The temperature distribution within the viscometer was monitored with the aid of a series of thermocouples positioned on the wall of the viscometer. The viscometer had a small positive temperature gradient to safeguard against convection. The uncertainty of the temperature was less than ± 50 mK. Pressure was measured by a transducer (Wide Plus Precision Instruments Co., Ltd., model: Wide Plus-8) with the maximum operating pressure of 6 MPa, and the uncertainty of the pressure was ± 6 kPa.

To obtain the accurate experimental viscosity data, the period of oscillation T and the logarithmic decrement of damping Δ must be determined precisely. In this work, a laser was placed at a distance about 2.0 m from the apparatus, and a beam produced by the laser aimed at the glass mirror inside the viscometer. Laser light reflected from the mirror sweeps past two stationary photoresistances, one located near the rest position of the oscillation beam and the other at an arbitrary offset angle. The period of oscillation T and the logarithmic decrement of damping Δ can be obtained from the time intervals between the two photoresistances. The detailed description was given by Kestin and Khalifa.¹⁵

Experimental Section

Fluid Samples. The sample of HFC245fa was provided by Zhejiang Fluoro-Chemical Technology Research Institute, China. The mass fraction purity of HFC245fa was better than 99.95

Table 3. Experimental Data of the Gaseous Viscosity of HFC245fa

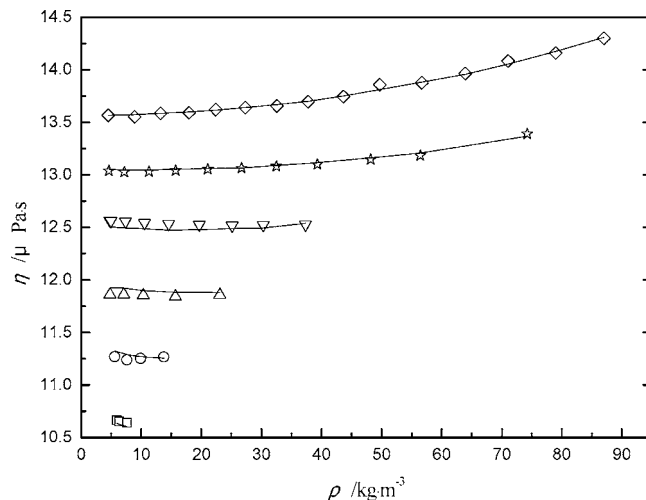
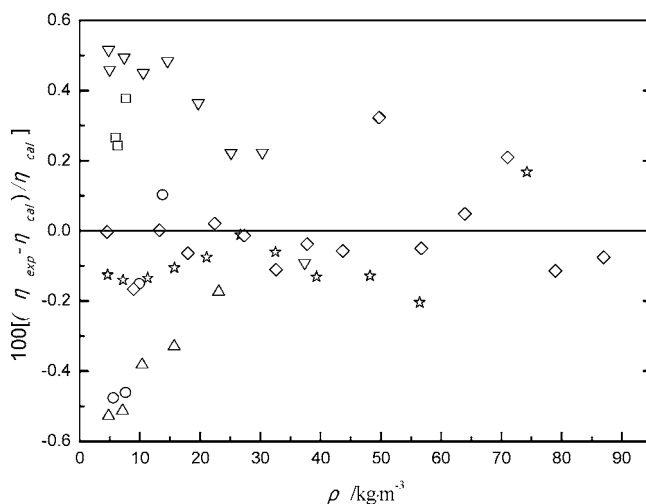
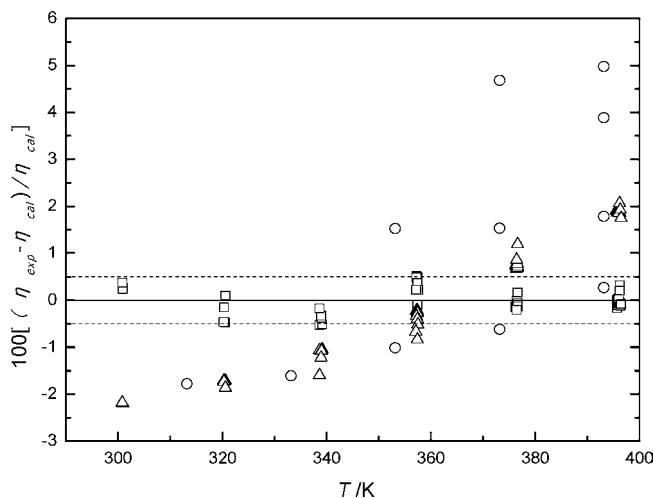
T K	P MPa	ρ $\text{kg}\cdot\text{m}^{-3}$	η $\mu\text{Pa}\cdot\text{s}$
300.93	0.107	5.966	10.664
300.88	0.113	6.315	10.653
300.81	0.136	7.652	10.641
320.53	0.108	5.582	11.271
320.26	0.145	7.592	11.239
320.33	0.186	9.903	11.254
320.58	0.254	13.766	11.268
338.61	0.100	4.804	11.862
339.15	0.145	7.105	11.863
339.02	0.207	10.345	11.855
338.98	0.307	15.709	11.843
338.61	0.435	23.103	11.857
357.23	0.104	4.791	12.562
357.39	0.108	4.975	12.559
357.38	0.159	7.391	12.554
357.40	0.224	10.556	12.540
357.23	0.305	14.600	12.532
357.43	0.403	19.699	12.522
357.52	0.503	25.129	12.515
357.15	0.592	30.324	12.520
357.43	0.708	37.345	12.525
376.46	0.107	4.640	13.036
376.25	0.164	7.207	13.026
376.38	0.254	11.301	13.029
376.54	0.348	15.758	13.039
376.61	0.457	21.082	13.051
376.39	0.567	26.708	13.064
376.58	0.676	32.514	13.080
376.64	0.797	39.332	13.099
376.61	0.945	48.215	13.144
376.43	1.071	56.476	13.182
376.63	1.312	74.258	13.389
395.60	0.109	4.517	13.567
395.66	0.213	8.918	13.551
395.77	0.311	13.216	13.585
395.80	0.417	17.953	13.590
395.85	0.512	22.377	13.619
395.93	0.616	27.308	13.639
395.93	0.723	32.599	13.655
395.81	0.823	37.782	13.695
396.00	0.934	43.668	13.743
396.24	1.044	49.733	13.857
396.22	1.164	56.717	13.875
396.02	1.280	63.927	13.963
396.17	1.390	71.049	14.083
396.35	1.505	78.958	14.159
396.46	1.614	86.997	14.298

Table 4. Coefficients of Equation 11

	$j = 0$	$j = 1$	$j = 2$
$i = 0$	-0.238545	1.57085	-0.320758
$i = 1$	-0.286859	0.432582	-0.163133
$i = 2$	0.064871	-0.101552	0.0398941

%, as indicated by analysis with a gas chromatograph (Agilent Technologies 6890N). A flame ionization detector (FID) and a capillary column (GS-GASPRO, model Agilent 113-4362) were used for the analysis with the carrier hydrogen at $4.0 \text{ mL}\cdot\text{min}^{-1}$, and the oven temperature and the detector temperature are (423 and 473) K, respectively. The sample of HFC245fa was not purified further.

Calibration and Testing. Prior to making the viscosity measurements, the viscometer was calibrated with nitrogen to determine the edge-correction factor C . The nitrogen was provided by Messer Co., Ltd., and the mass fraction purity was better than 99.999 %. The viscosity values of nitrogen were taken from Lemmon and Jacobsen¹⁶ and the density data of nitrogen from Lemmon et al.¹⁷ The values of the edge-correction factor C as a function of boundary layer δ are shown in Figure 2. The maximum deviation and the absolute average deviation

**Figure 4.** Viscosity of HFC245fa as a function of density: \square , 300 K; \circ , 320 K; Δ , 338 K; ∇ , 357 K; \star , 376 K; \diamond , 396 K; —, eq 11.**Figure 5.** Deviations of experimental viscosity values of HFC245fa from eq 11: \square , 300 K; \circ , 320 K; Δ , 338 K; ∇ , 357 K; \star , 376 K; \diamond , 396 K.**Figure 6.** Deviations of viscosity data of HFC245fa from eq 11: \square , this work; \circ , Geller et al.;⁸ Δ , calculated with REFPROP.¹⁷

between the fitted values and the calibration curve were 0.71 % and 0.31 %, respectively. The value determined by the calibration was $C_{(\delta=\infty)} = 1.2260$.

At the same time, to check the performance of the apparatus, the viscosity of argon was measured at the temperature of 300

K and at pressures up to 4.5 MPa. The mass fraction purity of the sample (provided by Messer Co., Ltd.) was better than 99.99 %. The density of argon was obtained from REFPROP.¹⁷ The measurement results are listed in Table 2. Compared to the calculated values of viscosity of argon from Lemmon and Jacobsen,¹⁶ the maximum deviation was 0.87 % and the mean deviation was 0.37 %. Taking all factors into account, the expanded uncertainty of the measurements was estimated to be within ± 2.0 % with a coverage factor of $k = 2$.

Results and Discussion

The viscosity of gaseous HFC245fa was measured at temperatures ranging from (300 to 396) K and at pressures up to 1.6 MPa. In total, 47 data points were obtained along six quasi-isotherms, and the distribution in temperature–pressure diagram was shown in Figure 3. The results were presented in Table 3 and shown in Figure 4. The experimental values of gaseous viscosity of HFC245fa were correlated as a function of temperature and density. The density of gaseous HFC245fa was determined from REFPROP 7.1.¹⁷ The correlation was obtained using a least-squares method to the following equation

$$\eta = \eta_0 \sum_{i=0}^2 \sum_{j=0}^2 b_{ij} (\rho/\rho_0)^i (T/T_0)^j \quad (11)$$

where T_0 , ρ_0 , and $\eta_0(T_0, \rho_0)$ are selected reference values. In this work, the values of T_0 , ρ_0 , and η_0 were 300.93 K, 5.966 kg·m⁻³, and 10.664 μ Pa·s, respectively. The coefficients were listed in Table 4. The calculated results from eq 11 were also shown in Figure 4 via the solid lines. The deviations between the experimental data and calculated values were shown in Figure 5. The maximum relative deviation and the average relative deviation of experimental data from eq 11 were 0.53 % and 0.21 %, respectively.

The data obtained by Geller et al.⁸ and the corresponding calculated results with REFPROP¹⁷ were compared in this work. Figure 6 shows the deviations from eq 11. It can be found that Geller's data and NIST data have a similar deviation trend. The reason may be attributed to the equation parameters of HFC245fa viscosity in REFPROP being based on Geller's data. However, the maximum deviation is within 5.0 %.

Conclusions

The viscosity of gaseous HFC245fa was measured with an oscillating disk viscometer of the Maxwell type in the temperature range from (300 to 396) K along six quasi-isotherms and pressures up to 1.6 MPa. The measured data were correlated as a function of temperature and density with the average deviation of 0.21 % and the maximum deviation of 0.53 %.

Acknowledgment

We are grateful to Prof. W. A. Wakeham, University of Southampton, U.K., for his significant suggestions and kind help.

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Received for review March 19, 2009. Accepted June 25, 2009. This work has been supported by the National Natural Science Foundation of China (Grant 50836004) and the Foundation for the Author of National Excellent Doctoral Dissertation (Grant 200540).

JE900279Z