Surface Tension of Pentafluoroethane (HFC-125)

M. F. Liu,[1] **L. Z. Han,**[1] **and M. S. Zhu**[1,2]

A set of accurate surface-tension data for HFC-125 has been obtained experimentally with both an absolute capillary rise technique and a differential capillary rise technique in the temperature range of 233.15–333.15 K. The purity of the experimental HFC-125 sample is 99.98 wt%. The two sets of experimental results with an absolute capillary rise method agree well with each other and, also, with the experimental results with a differential capillary rise method. The absolute deviations of experimental results with these two methods are within 0.01 mN · m^{-1} The relative deviation are within 0.2%. A van der Waals surface-tension correlation is also proposed.

1. INTRODUCTION

On November 25, 1992, the Copenhagen revisions to the Montreal Protocol amended that hydrochlorofluorocarbon (HCFC) consumption will be phased out by 2030. A hydrochlorocarbon (HFC) whose ozone depletion potential (ODP) value is zero, to replace hydrochlorofluoro-carbon (HCFC), has to be found. Binary and/or ternary mixtures (such as HFC-32/HFC-125, HFC-32/HFC-125/HFC134a) with difluoromethane (HFC-32), pentafluoroethane (HFC-125), and 1,1,1,2-tetrafluoroethane (HFC-134a) as components are thought to be the most promising alternatives for HCFC-22. Thermodynamic properties (such as PVT, vapor pressure, velocity of sound, ideal-gas heat capacity, surface tension, etc.) for HFC-134a have been measured by Zhu et al. [1–4]. Vapor pressure and surface-tension data for HFC-32 have also been reported by Zhu et al. [5, 6]. Unfortunately, reliable thermophysical property data for HFC-125 are still limited. In particular, only one set of surface-tension data in the

---

[1] Department of Thermal Engineering, Tsinghua University, Beijing 100084, P.R. China.
[2] To whom correspondence should be addressed.

temperature range from 297.73 to 338.66 K and three expressions for HFC-125 have been reported by Schmidt and Moldover [7] before this work.

Surface-tension is an important thermophysical property, especially with respect to heat transfer through a heat exchanging surface with bubbles or fluid drops on it. Therefore, this paper presents 21 surface-tension measurements for HFC-125 over the temperature range from 233.15 to 333.15 K.

Among the methods of surface-tension measurements available, the capillary rise method is preferred. The three sets of HFC-134a surface-tension data by Chae et al. [8], Okada et al. [9], and Zhu et al. [4] and one set of HFC-32 surface-tension data by Zhu and Lu [6] have all been measured with this method.

The capillary rise method was also used in the present work. For increasing the confidence, both an absolute capillary rise technique and a differential capillary rise technique were adopted in this work at the same time over the temperature range from 233.15 to 333.15 K. The results were consistent with each other. The absolute deviations between these two mthods are within $0.01\ mN \cdot m^{-1}$ and relative deviations are within 0.2%. Based on these data, a van der Waals-type surface-tension correlation for HFC-125 is proposed.

2. APPARATUS

The apparatus used here has been described by Zhu et al. [4, 6] and is shown in Fig. 1. To measure the surface tension precisely, we used a direct optical measurement system, which includes a movable coordinate frame, a telescope, and an accurate displacement sensor. The meniscus in capillaries 1 and 2 and the bulk meniscus in the sample cell at each temperature were measured accurately by the displacement sensor, respectively, then displayed on the digital readout in millimeters. The precision of the accurate displacement sensor and digital readout unit for measuring the capillary rise was $\pm 1\ \mu m$. The temperature of the cell was controlled by a thermostated bath in the range from 233.15 to 333.15 K. The temperature uncertainty was ± 0.01 K. Before each measurement, the capillaries were carefully washed and were sealed in the cell vertically.

The surface tension as a function of the capillary rise was determined as follows [10]:

$$\sigma = \frac{(\rho_1 - \rho_v)\, g}{2}\, r \left[h - h_0 + \frac{r}{3} - 0.1288\, \frac{r^2}{(h-h_0)} + 0.13122\, \frac{r^3}{(h-h_0)^2} \right] \qquad (1)$$
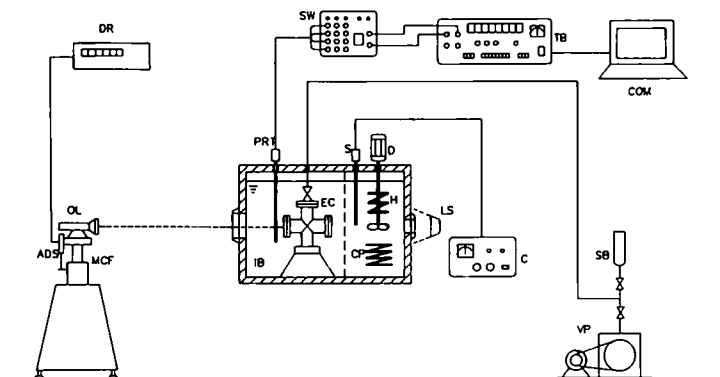
Fig. 1. Surface-tension apparatus. MCF, movable coordinate frame; OL, optical level instrument; ADS, accurate displacement sensor; DR, digital readout; EC, experimental cell; IB, thermostated bath; PRT, Pt resistance thermometer; SW, selector switch; TB, automatic thermometer bridge; COM, computer; S, thermal-sensitive resistance sensor; C, controller; D, dynamic-electric stirrer; H, heater; CP, cooling pipe; VP, vacuum pump; SB, sample bottle; LS, light source.

Here r is the radius of the capillary tube, $h - h_0$ is the capillary rise, h_0 is the height of the bulk meniscus, ρ_1 and ρ_v are the densities of the saturated liquid and vapor, respectively, and g is the acceleration due to gravity. In Eq. (1), ρ_1 was calculated from the saturated liquid-density correlation and ρ_v was calculated from the saturated vapor-pressure correlation and the equation of state proposed by Barrett and Candau [11].

When the inner radius of the capillary is less than the height of capillary rise, the meniscus approaches a spherical surface and then the surface-tension value calculated from Eq. (1) is correct. The predicted values of surface tension for HFC-125 from a corresponding-states equation [12] show that it is smaller than that of other alternatives. If a capillary with the larger radius is adopted, the height of capillary rise is lower and Eq. (1) will not be suitable for calculating the surface tension of HFC-125. Therefore, the two smaller radii of the capillaries were adopted in this work.

The inner radii of the capillaries were determined by partially filling the capillaries with mercury slugs of different mass. For each mass, the slug was moved along the capillary tube. The length of the slug at different positions was measured with a traveling microscope with an accuracy of ± 0.1 μm. The mass of mercury slug was determined by a precision electrical balance accurate to ± 0.1 mg. Combining the length and mss of the slug, we calculated the average radius at each position. From the results corresponding to different mercury slugs, a consistent set of values was

developed for each capillary radius. The inner radii of the capillaries were represented as a function of distance in the longitudinal direction from one end of the capillary. The average bore radii of the capillaries in our apparatus are $r_1 = 0.259 \pm 0.001$ mm and $r_2 = 0.127 \pm 0.001$ mm.

3. RESULTS

The measurements were made every 5 K in the temperature range 233.15–333.15 K. For each measurement, the height of the meniscus of the two capillaries, h_1 and h_2, and the height of the bulk meniscus, h_0, were measured. Then the capillary rise, $(h_1 - h_0)$ and $(h_2 - h_0)$, can be obtained and two sets of HFC-125 surface-tension data, σ_1 and σ_2, can be calculated from Eq. (1). These results are presented in Table I. Table I shows that the two experimental sets are consistent with each other. The average values of surface tension, σ_{abs}, calculated from σ_1 and σ_2 are also given in Table I. Using the differential capillary rise method, the height of the bulk

Table I. Experimental Capillary Rise and Surface Tension of HFC-125

T (K)	ρ_1 (kg·m^{-3})	ρ_v (kg·m^{-3})	$h_1 - h_0$ (mm)	$h_2 - h_0$ (mm)	σ_1 (mN·m^{-1})	σ_2 (mN·m^{-1})	σ_{abs} (mN·m^{-1})	σ_{rel} (mN·m^{-1})
233.15	1483.7	9.880	6.639	13.70	12.605	12.607	12.606	12.609
238.15	1466.3	12.14	6.331	13.07	11.867	11.866	11.866	11.865
243.15	1447.2	14.78	6.029	12.45	11.139	11.136	11.137	11.132
248.15	1426.5	17.86	5.730	11.84	10.419	10.415	10.417	10.411
253.15	1406.5	21.43	5.426	11.22	9.7083	9.7080	9.7082	9.7077
258.15	1387.0	25.55	5.118	10.59	9.0092	9.0085	9.0089	9.0079
263.15	1364.3	30.29	4.821	9.983	8.3235	8.3237	8.3236	8.3240
268.15	1342.3	35.73	4.513	9.357	7.6404	7.6436	7.6420	7.6466
273.15	1321.0	41.96	4.206	8.725	6.9799	6.9795	6.9797	6.9791
278.15	1297.0	49.10	3.904	8.109	6.3305	6.3312	6.3309	6.3318
283.15	1272.3	57.27	3.596	7.484	5.6873	5.6915	5.6894	5.6955
288.15	1246.9	66.65	3.286	6.849	5.0589	5.0621	5.0605	5.0652
293.15	1219.5	77.43	2.982	6.221	4.4535	4.4521	4.4528	4.4507
298.15	1190.1	89.87	2.673	5.586	3.8573	3.8539	3.8556	3.8506
303.15	1160.1	104.32	2.365	4.961	3.2876	3.2876	3.2876	3.2876
308.15	1126.1	121.26	2.048	4.318	2.7234	2.7269	2.7252	2.7302
313.15	1089.3	141.36	1.733	3.673	2.1887	2.1919	2.1903	2.1969
318.15	1049.3	165.67	1.410	3.008	1.6763	1.6773	1.6788	1.6783
323.15	1002.0	196.00	1.082	2.337	1.1917	1.1932	1.1925	1.1947
328.15	945.18	235.74	0.756	1.673	0.7553	0.7569	0.7561	0.7585
333.15	870.32	293.51	0.419	0.978	0.3653	0.3657	0.3655	0.3660

meniscus, h_0, is eliminated numerically by combining the calculated surface tension from Eq. (1) corresponding to two capillaries. The surface-tension data, σ_{rel}, of HFC-125 with the differential capillary rise method are also shown in Table I. From Table I, we can see that they agree satisfactorily with the values, σ_{abs}. The absolute deviations and the relative deviations between these two methods are within $0.01\ mN \cdot m^{-1}$ and 0.2 %, respectively.

According to the capillary rise data at the temperature range from 297.73 to 338.66 K, a fitted equation has been proposed by Schmidt and Moldover [7]. In Eq. (2), T_c was

$$a^2 = 5.26\left(1 - \frac{T}{T_c}\right)0.935 \tag{2}$$

the critical temperature, 339.33 K, and a^2 was capillary rise parameter. The quantity a^2 is calculated from Eq. (3).

$$a^2 = r\left[h - h_0 + \frac{r}{3} - 0.1288\,\frac{r^2}{(h - h_0)} + 0.1312\,\frac{r^3}{(h - h_0)^2}\right] \tag{3}$$

For comparison purposes, the deviations of the capillary rise parameter measured by us and Schmidt and Moldover [7] from Eq. (2) are plotted in Fig. 2. From Fig. 2, the deviations with our data and Schmidt and Moldover's data are within ± 0.015 and $\pm 0.010\ mm^2$, respec-
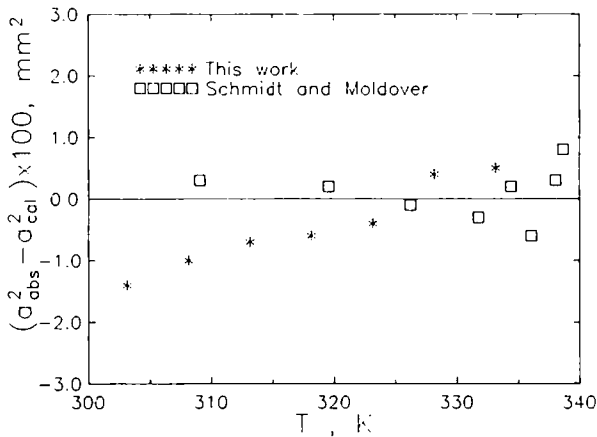

Fig. 2. Deviations of the capillary rise parameter from the fitted equation proposed by Schmidt and Moldover [7].
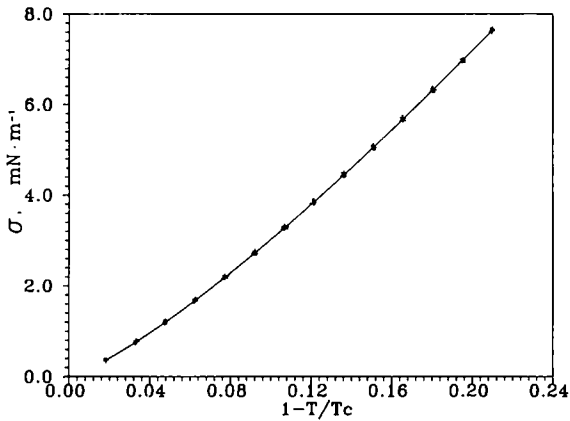
Fig. 3. The relation between the reduced temperature and the surface tension for HFC-125.

tively, of the temperature range from 300 to 333.15 K that is valid for Eq. (2). Our results are consistent with theirs.

The surface tension is normally correlated as a function of temperature for HFC-125 by a van der Waals-type correlation:

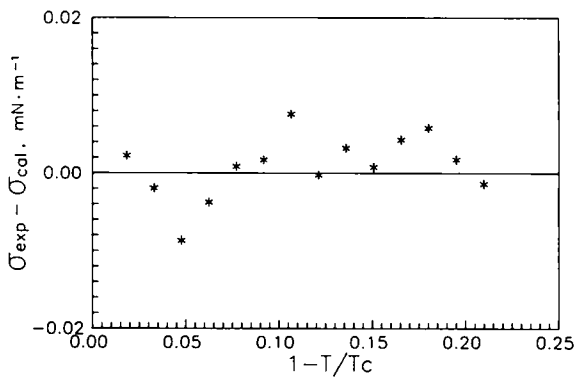$$\sigma = \sigma_0 \left(1 - \frac{T}{T_c}\right)^n \tag{4}$$

Fig. 4. Absolute deviations of the experimental data from Eq. (2).
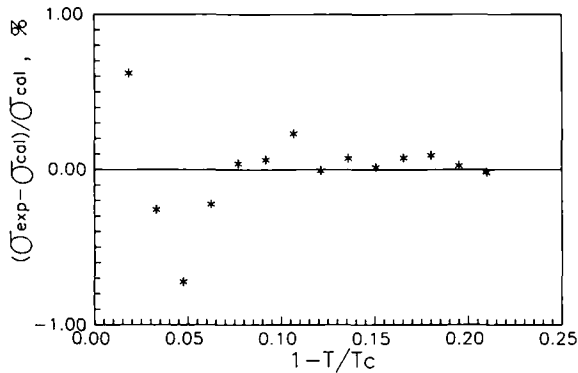
Fig. 5. Relative deviations of the experimental data from
Eq. (2).

In Eq. (4), σ_0 and n are constants and $T_c = 339.4$ K is the critical temperature (obtained from McLinden [13]). From the data of σ_{abs} in Table I, we find that $\sigma_0 = 53.9553$ mN $\cdot$ m^{-1} and $n = 1.25198$.

Figure 3 shows the relation between the reduced temperature and the surface tension. Figures 4 and 5 show the absolute deviations and relative deviations of the experimental data from Eq. (4), respectively. From Figs. 4 and 5, the absolute deviations are within ± 0.01 mN $\cdot$ m^{-1}, the relative deviations are within 0.8%, and the root-mean-square deviation (RMS Dev) of the surface-tension data, σ_{abs}, presented in Table I from Eq. (4), is 0.28%.

4. SUMMARY

The surface tension of HFC-125 is smaller than that of HFC-134a and HFC-32. Table II shows the results for these alternatives at 303.15 K. The surface tension of HFC-125 was measured in the temperature rage from 233.15 to 333.15 K. The results and a surface-tension correlation are presented. The measured data obtained by using absolute and relative capillary rise methods are very consistent.

Table II. Surface Tension of HFC-134a, HFC-32, and HFC-125 at 298.15 K

	HFC-134a	HFC-32	HFC-125
σ (mN $\cdot$ m^{-1})	7.960	6.683	3.85

ACKNOWLEDGMENTS

REFERENCES

1. M. S. Zhu, Y. D. Fu, and L. Z. Han, *Fluid Phase Equil.* **80**:149 (1992).
2. M. S. Zhu, J. Wu, and Y. D. Fu, *Fluid Phase Equil.* **80**:99 (1992).
3. M. S. Zhu, L. Z. Han, K. Z. Zhang, and T. Y. Zhou, *Int. J. Thermophys.* **14**:1039 (1993).
4. M. S. Zhu, L. Z. Han, and C. X. Lu, *Fluid Phase Equil.* **86**:363 (1993).
5. M. S. Zhu, J. Li, and B. X. Wang, *Int. J. Thermophys.* **14**:1221 (1993).
6. M. S. Zhu and C. X. Lu, *J. Chem. Eng. Data* **39**:11 (1994).
7. J. W. Schmidt and M. R. Moldover, *J. Chem. Eng. Data* **39**:39 (1994).
8. H. B. Chae, J. W. Schmidt, and M. R. Moldover, *J. Chem. Eng. Data* **35**:6 (1990).
9. M. Okada, T. Umayahave, M. Hattori, and K. Watanabe, *Proc. Tenth Japan. Symp. Thermophys. Prop.* (Shizuoka Univ., Johiku Hamamatsu, Japan, 1989), p. 60.
10. O. M. Rayleigh, *Proc. R. Soc. London Ser. A* **92**:184 (1916).
11. M. Barret and Y. Candau, *Proc. 1992 Int. Refrig. Conf.—E Efficiency and New Refrigerants*, D. R. Tree and J. E. Braun, eds. (Purdue University, July 14–17, 1992), p. 433.
12. D. I. Hakim, D. Steinberg, and L. I. Stiel, *Ind. Eng. Chem. Fundam.* **10**:174 (1971).
13. M. O. McLinden, *Int. J. Refrig.* **13**:149 (1990).