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DOE/CE/23810-66A

THERMOPHYSICAL PROPERTIES OF HCFC ALTERNATIVES

Quarterly Report

1 October 1995 - 31 December 1995

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January 1996

Prepared for
The Air-Conditioning and Refrigeration Technology Institute
Under
ARTI MCLR Project Number 660-50800

This research project is supported in part by a grant from the U.S. Department of Energy, Office of Building Technology (Grant number DE-FG02-91CE23810: Materials Compatibilities and Lubricants Research on CFC-Refrigerant Substitutes). Federal funding supporting this project constitutes 93.57% of allowable costs. Funding from the air-conditioning and refrigeration industry supporting the project consists of direct cost sharing of 6.43% of allowable costs; and significant in-kind contributions.

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THERMOPHYSICAL PROPERTIES OF HCFC ALTERNATIVES**ARTI MCLR Project Number 660-50800****W.M. Haynes****Thermophysics Division****National Institute of Standards and Technology****ABSTRACT**

Numerous fluids and fluid mixtures have been identified as promising alternatives to the HCFC refrigerants, but, for many of them, reliable thermodynamic data do not exist. In particular, reliable thermodynamic properties data and models are needed to predict the performance of the new refrigerants in heating and cooling equipment and to design and optimize equipment to be reliable and energy efficient. The objective of this project is to measure, with high accuracy, selected thermodynamic properties data for two pure refrigerants and nine refrigerant blends; these data will be used to fit equations of state and other property models which can be used in equipment design. The new data will fill in gaps in the existing data and resolve problems and differences that exist in and between existing data sets. Most of the studied fluids and blends are potential replacements for HCFC-22 and/or R502; in addition, one pure fluid and one blend are potential replacements for CFC-13 in low temperature refrigeration applications.

SCOPE

This project involves the measurement of primary thermodynamic data for eight binary mixtures and one ternary mixture (R125/134a; R32/143a; R125/143a; R143a/134a; R32/290; R125/290; R290/134a; R41/744; and R32/125/134a). These data will consist of simultaneous measurements of the coexisting liquid and vapor densities and coexisting liquid and vapor compositions as well as the bubble point pressures over wide ranges of temperature and composition. These data will be used to determine the mixing parameters, including any temperature and/or composition dependence, for the Carnahan-Starling-DeSantis (CSD) equation of state and the extended corresponding states (ECS) model. Primary data will also be measured for the pure fluid HFC-41. These measurements will include the determination of vapor pressure; liquid density; liquid, two-phase, and ideal gas heat capacities; vapor sound speeds and virial coefficients; and a determination of the critical point parameters. These data will cover wide ranges of temperature and pressure and will be used (together with available literature data) to fit equations of state and other models of the thermodynamic properties. The original proposal called for similar measurements of primary data for HFC-245ca; since work on this fluid has been funded by another sponsor, comprehensive mixture data for the binary system R125/143a have been substituted as recommended by the MCLR Advisory Committee. During the past quarter, we have carried out the following tasks: (a) completion of development of new state-of-the-art vapor-liquid equilibrium (VLE) apparatus, (b) measurements of coexisting densities, bubble point pressures, and liquid and vapor compositions of R32/134a and R32/125/134a systems with new VLE apparatus, (c) completion of isochoric PVT measurements on HFC-41 (fluoromethane) from 132 to 400 K (-222 to 260°F) at pressures up to 35 MPa (5100 psia), (d) vapor pressure measurements on HFC-41 from 132 to 317 K (-222 to 111°F),

(e) initiation of isochoric PVT measurements on the R41/744 system, and (f) initiation of vapor-liquid equilibrium and coexisting density measurements on the R32/125 system.

SIGNIFICANT RESULTS

Primary mixture data for binary mixtures of relatively volatile components (R125/134a; R32/143a; R125/143a; R143a/134a; R32/290; R125/290; R134a/290)

Performance tests and calibrations were completed for the new vapor-liquid equilibrium liquid-bath apparatus during the past quarter. The apparatus was used to repeat and extend measurements for the binary R32/134a system (supported by the Department of Energy). These measurements demonstrated the significantly improved performance of the new apparatus compared to the previous air-bath apparatus. The vapor composition measurements from the new apparatus for the binary mixture of R32/134a were a factor of ten better than the measurements from the previous apparatus at the lower temperatures and a factor of two better than the measurements from the previous apparatus at the higher temperatures. The scatter in the bubble point pressures was also significantly reduced.

The bubble point pressures, coexisting liquid and vapor compositions, and coexisting densities were remeasured for R32/134a from 280 to 340 K (44 to 152°F) in 15 K (27°F) increments. Additional data were taken at selected temperatures in the low temperature region so that the data could be compared more directly with the results from other laboratories. Figures 1 and 2 show the results from the new apparatus compared to literature data discussed in a previous report. The improvement in the vapor compositions and the bubble point pressures is significant. The data are in agreement with the bubble point pressures of Defibaugh [National Institute of Standards and Technology, private communication] and of Kleemiss [University of Hannover, private communication] and the vapor composition data of Higashi [Iwaki Meisei University, private communication] and of Kleemiss. The bubble point pressures of Fujiwara *et al.* [Fujiwara *et al.* 13th Japan Symposium Thermophysics Properties A116:61 (1992)] are lower than the other data sets, and the bubble point pressures of Widiatmo *et al.* [Widiatmo, J.V., Sato, H., and Watanabe, K., Fluid Phase Equilibria 99:199 (1994)] tend to be higher than the other data sets.

The performance of the new apparatus is a strong indication that the temperature gradient problems discussed in a previous report were the main sources of error in the measurements performed with the previous apparatus. The gas chromatograph (GC) from the previous apparatus is being used with the new apparatus. The same GC column and calibration curves were used in the composition analysis for both apparatus. The samples of HFC-32 and HFC-134a used in both sets of measurements came from the same supply cylinders. The same type of rotary GC valves were used for sampling the vapor and liquid in both apparatus. The three major differences between the two apparatus include the temperature gradients across the system, the orientation of the densimeters, and the sampling method used to withdraw liquid and vapor samples. The orientation of the densimeters would not affect the vapor-liquid equilibrium measurement. The two different sampling methods employed in the two apparatus should give the same results. The only condition under which the trapped sampling method would perform differently from the capillary method would be for a temperature gradient that caused condensation or vaporization near the GC valves. The trapped sampling method would then be measuring the composition of a sample that is not in equilibrium with the contents of the main cell. All of the proposed reasons for the differences observed in the data from the two apparatus are related to the temperature gradients in the previous apparatus that produced pockets of material that were not in equilibrium with the material in the main cell. If these

pockets formed near the pressure transducer or the GC valves, the measurement would have been taken on samples not in equilibrium.

Measurements on the R32/125 system have been initiated in the new apparatus. These will be completed in two weeks. Then, we will repeat measurements on the R32/143a, R32/290, R134a/290, and R125/290 systems. We will repeat as many measurements as necessary for each system. If we find that the previous apparatus performed satisfactorily for a certain system, we will repeat only a few measurements. We will then study the R134a/143a, R125/143a, and R134a/125 systems.

Primary mixture data for a ternary mixture of relatively volatile components (R32/125/134a)

The bubble point pressures and coexisting liquid densities for a ternary mixture of R32/125/134a (supported by ICI) were repeated at temperatures from 219 to 312 K (-65 to 102°F) on the new apparatus. The mixture used in the new apparatus came from the same standard reference mixture bottle that was used in the measurements with the previous apparatus. These new results have been combined with the data from the previous apparatus for temperatures where temperature gradients did not pose a problem. For the previous apparatus temperature gradients were sufficiently small only at temperatures above 284 K (52°F). The new data cover a temperature range from 221 to 345 K (-62 to 161°F).

Figure 3 compares the new results to other literature and unpublished data near the same composition. The results are significantly improved from the results obtained with the previous air-bath apparatus that was characterized by significant temperature gradients. Again, this is an indication of the uncertainty that even small temperature gradients can introduce into the measurement of the properties of these refrigerant mixtures. The data at the lowest two temperatures for the new apparatus appear to be diverging slightly from the data of ICI. The absolute pressure at these temperature is approximately 0.1 MPa (14.7 psia). This low pressure is less than 10% of the full range of the pressure transducer. The uncertainty of the pressure transducer in this region is greater than at higher pressures and could account for the deviations seen in Figure 3.

The ternary mixture will be studied in greater detail over the temperature range from 280 to 340 K (44 to 152°F). Several compositions will be measured on each isotherm in 15 K (27°F) increments. These data will be combined with the relevant binary mixture data and this single composition ternary mixture data to define the two-phase region.

Primary mixture data for binary mixture of very low boiling components (R41/744)

Isochoric PVT measurements have been initiated on an equimolar mixture of R41/744. These measurements will cover a temperature range from 192 to 400 K (-114 to 260°F) at pressures to 35 MPa (5100 psia).

The R41/744 mixture is of interest as a replacement for CFC-13 and HFC-23 in ultra-low temperature refrigeration systems. The relatively high triple-point temperature of carbon dioxide (216.6 K, -69.8°F) precludes the use of pure carbon dioxide in many such applications. The freezing point of the mixture is not known. We will investigate the freezing point of the R41/744 mixture by one or more methods. Direct observation of freezing points is possible in our new liquid-bath VLE apparatus, but its lower temperature limit of roughly 210 K (-82°F) will

restrict its applicability to CO₂-rich compositions. But this would, at least, indicate the trend of the freezing point with increased HFC-41 composition. We can obtain an upper bound on the freezing point for the equimolar mixture using the isochoric PVT apparatus. We would cool the PVT cell to a given temperature and attempt to fill the cell; if the sample flows in readily, the cell temperature is above the freezing point. By choosing different initial temperatures for the several fillings required for the scheduled PVT measurements, an upper bound for the freezing point can be obtained. The PVT apparatus operates down to liquid nitrogen temperatures. Finally, if an accurate determination of the freezing point is required, we can conduct additional measurements in the low-temperature isochoric calorimeter. This would involve slowly cooling the liquid sample at a steady rate (approximately 2 K · hr⁻¹) until the formation of a solid phase occurs. The temperature at this point will be determined from a sharp break in a graph of the recorded temperatures and times, where the temperature will reach a plateau value for the elapsed time needed to reach equilibrium between the solid and liquid phases.

Comprehensive data for the R143a/125 mixture

Comprehensive isochoric PVT measurements were completed earlier for an equimolar mixture of R143a/125. C_v measurements will be initiated during the next quarter.

Primary data for a very low-boiling fluid (HFC-41)

Isochoric PVT measurements have been completed for fluoromethane (HFC-41) on samples from a specially purified supply cylinder that contains no detectable amounts of diethyl ether, light organic, or halocarbon impurities, as determined by our gas chromatography/mass spectrometry analysis. Densities were measured with an isochoric PVT apparatus at 445 points in the temperature range from 132 to 400 K (-222 to 260°F) with pressures up to 35 MPa (5100 psi). The lowest reported temperature is slightly above the published freezing point temperature of 131.4 K (-223.1°F). The measurements were carried out on a total of 20 runs at different filling densities. These data are in the liquid and gaseous phases. The pressures, temperatures, and densities are presented in Tables 1 and 2, and the locations of the measurements are shown in Figure 4. Since no published data existed below 273 K (32°F) before this work, the reported measurements extend the temperature range of density data available for fitting an equation of state by more than 140 K (252°F).

There also existed a large region in published vapor pressure data for HFC-41, between the temperatures 211 and 253 K (-80 to -4 °F), where no reliable data could be found. During the past quarter, vapor pressures were measured in the temperature range from 132 to 317 K (-222 to 111°F) using the isochoric PVT apparatus. The data at 39 temperatures are reported in Tables 3 and 4. Because the reported data overlap and close the gap between sets of published data, they provide a single source of reliable vapor pressures with which we can intercompare all of the published measurements, and also fit a vapor pressure equation which covers the entire vapor pressure curve.

Vapor pressures and coexisting densities were measured for HFC-41 with the new vapor-liquid equilibrium apparatus. These data cover a range from 218 to 312 K (-67 to 102°F). These measurements were carried out on the new apparatus to test its performance and to obtain results for the pure components of a mixture to be studied on the same apparatus. These vapor pressures agreed within experimental uncertainty ($\pm 0.1\%$) with those in Tables 3 and 4 from the isochoric PVT apparatus. The coexisting densities for HFC-41 will not be reported until sensitivity tests for the densimeter calibration equations are complete.

A new spherical resonator that will be used for sound speed measurements on HFC-41 is essentially ready for measurements. Gaseous argon is being used to determine the radius of the sphere. The temperature control system has been tested; it can provide temperature control to ± 1 mk. Sound speed measurements on HFC-41 will be initiated during the next quarter.

COMPLIANCE WITH AGREEMENT

NIST has complied with all terms of the grant agreement modulo small shifts in the estimated level of effort from one property and/or fluid to another.

PRINCIPAL INVESTIGATOR EFFORT

Dr. W.M. Haynes is the NIST Principal Investigator for the MCLR program. During the fourth quarter of calendar year 1995, Dr. Haynes devoted approximately one week to planning this project, monitoring and reviewing the research, and preparing the report. The project involves multiple researchers and capabilities in Gaithersburg, MD and Boulder, CO.

Figure 1: Comparison of bubble point pressures for the R32/134a system; the baseline is from an extended corresponding states (ECS) model in REFPROP.

Figure 2: Comparison of vapor compositions for the R32/134a system; the baseline is from an extended corresponding states (ECS) model in REFPROP.

Figure 3: Comparison of bubble point pressures for the R32/125/134a system; the baseline is from an extended corresponding states (ECS) model in REFPROP.

Figure 4: Locus of PVT data for HFC-41.

APPENDIX A:
TABLES OF THERMOPHYSICAL PROPERTIES DATA

Table 1. Compressed Gas and Liquid-Phase PVT Data for Fluoromethane (HFC-41) in SI Units.

T	P	ρ
K	MPa	mol·dm ⁻³
132.000	3.7947	29.6103
132.999	5.9677	29.5999
134.000	7.6985	29.5807
135.000	9.2786	29.5551
136.000	11.4361	29.5441
136.999	13.7673	29.5369
138.000	16.1748	29.5309
138.999	18.6070	29.5257
139.999	21.0494	29.5209
140.999	23.5062	29.5163
142.000	25.9595	29.5120
143.000	28.4095	29.5079
143.999	30.8687	29.5038
144.999	33.3136	29.4999
142.000	3.8165	29.0602
142.999	5.8434	29.0505
144.000	7.5402	29.0338
144.999	8.9768	29.0074
145.999	10.9159	28.9959
146.999	13.0556	28.9885
148.001	15.2637	28.9826
149.000	17.5065	28.9775
150.000	19.7567	28.9728
151.000	22.0135	28.9684
152.000	24.2862	28.9642
153.000	26.5428	28.9602
154.000	28.8015	28.9563
155.000	31.0703	28.9525
156.001	33.3213	28.9488
154.000	3.8535	28.3931
155.000	5.7194	28.3842
155.999	7.3427	28.3700
157.001	8.6648	28.3437
157.999	10.3772	28.3310
158.999	12.2980	28.3235
159.999	14.3003	28.3177
160.999	16.3194	28.3126
161.999	18.3586	28.3081
163.000	20.4124	28.3038
163.999	22.4542	28.2998
165.000	24.5189	28.2959
165.999	26.5634	28.2922
166.998	28.6067	28.2886
168.000	30.6602	28.2850
168.999	32.6986	28.2815
170.000	34.7485	28.2781
167.998	3.8483	27.5995
168.999	5.5291	27.5916
169.999	7.0744	27.5797
170.998	8.3010	27.5556
172.000	9.7689	27.5404
173.000	11.4618	27.5324
173.999	13.2224	27.5265

Table 1. Compressed Gas and Liquid-Phase PVT Data for Fluoromethane (HFC-41) in SI Units (continued).

T	P	ρ
K	MPa	mol·dm ⁻³
174.999	15.0243	27.5215
175.999	16.8417	27.5171
176.999	18.6613	27.5129
177.999	20.4950	27.5090
179.000	22.3201	27.5053
179.999	24.1515	27.5018
180.998	25.9775	27.4983
181.999	27.8011	27.4949
182.999	29.6298	27.4916
184.000	31.4503	27.4884
184.999	33.2697	27.4852
185.999	35.0874	27.4820
184.000	3.8192	26.6703
185.000	5.3156	26.6634
186.000	6.7440	26.6536
187.000	7.9183	26.6346
188.001	9.1419	26.6152
189.001	10.5886	26.6063
190.001	12.1260	26.6001
191.001	13.6949	26.5952
192.000	15.2734	26.5908
193.000	16.8728	26.5867
194.000	18.4663	26.5830
195.001	20.0674	26.5794
196.000	21.6675	26.5760
197.000	23.2669	26.5727
198.000	24.8753	26.5695
198.999	26.4733	26.5663
200.001	28.0748	26.5633
201.000	29.6684	26.5602
202.001	31.2603	26.5573
203.000	32.8550	26.5543
204.000	34.4410	26.5514
200.000	3.7884	25.7064
201.000	5.1415	25.7001
202.000	6.4328	25.6920
203.001	7.5796	25.6782
204.000	8.6144	25.6565
205.000	9.8458	25.6457
206.000	11.1682	25.6392
207.001	12.5291	25.6341
207.999	13.9092	25.6297
209.001	15.2923	25.6258
210.000	16.6913	25.6221
211.999	19.4853	25.6154
214.000	22.2776	25.6092
216.001	25.0812	25.6032
218.001	27.8685	25.5975
220.002	30.6434	25.5920
222.001	33.4180	25.5866
220.002	3.6347	24.4215
221.000	4.7578	24.4164
222.001	5.8830	24.4101

Table 1. Compressed Gas and Liquid-Phase PVT Data for Fluoromethane (HFC-41) in SI Units (continued).

T	P	ρ
K	MPa	mol·dm ⁻³
222.999	6.9410	24.4015
224.000	7.8843	24.3851
224.999	8.8290	24.3677
226.001	9.9027	24.3591
227.001	11.0226	24.3534
228.002	12.1643	24.3488
229.001	13.3203	24.3448
230.000	14.4766	24.3411
232.000	16.8051	24.3346
234.000	19.1419	24.3286
236.001	21.4772	24.3230
238.001	23.8124	24.3176
239.999	26.1386	24.3124
242.002	28.4583	24.3074
244.002	30.7777	24.3024
246.001	33.0881	24.2976
248.002	35.4018	24.2928
240.000	3.8003	23.0354
241.001	4.7476	23.0309
241.999	5.6800	23.0256
243.000	6.5951	23.0190
244.000	7.4483	23.0087
245.000	8.2413	22.9906
246.000	9.0950	22.9788
247.000	10.0074	22.9721
247.999	10.9381	22.9673
249.000	11.8837	22.9632
249.998	12.8368	22.9596
252.001	14.7587	22.9532
253.999	16.6777	22.9474
255.998	18.5953	22.9421
258.000	20.5214	22.9371
260.000	22.4456	22.9322
261.999	24.3658	22.9275
264.000	26.2848	22.9229
265.999	28.2029	22.9183
268.002	30.1190	22.9139
270.002	32.0287	22.9094
271.999	33.9325	22.9051
260.000	3.8305	21.4467
261.001	4.5921	21.4430
261.998	5.3514	21.4388
263.000	6.1075	21.4338
263.999	6.8400	21.4275
265.000	7.5401	21.4177
266.001	8.2129	21.4018
266.999	8.9132	21.3911
268.001	9.6499	21.3847
269.000	10.3986	21.3801
270.000	11.1601	21.3762
272.001	12.6898	21.3697
273.999	14.2226	21.3641

Table 1. Compressed Gas and Liquid-Phase PVT Data for Fluoromethane (HFC-41) in SI Units (continued).

T	P	ρ
K	MPa	mol·dm ⁻³
275.999	15.7612	21.3590
277.999	17.3033	21.3542
280.002	18.8483	21.3496
281.999	20.3912	21.3452
283.998	21.9356	21.3409
286.000	23.4783	21.3367
288.000	25.0172	21.3325
289.999	26.5552	21.3285
292.000	28.0941	21.3244
294.000	29.6266	21.3204
296.000	31.1562	21.3165
298.000	32.6880	21.3126
299.999	34.2158	21.3087
280.001	4.7980	19.6641
281.000	5.3963	19.6605
281.999	5.9836	19.6565
283.002	6.5694	19.6517
283.999	7.1428	19.6455
285.999	8.2455	19.6224
287.999	9.3867	19.6077
289.999	10.5647	19.5998
292.002	11.7576	19.5938
294.002	12.9527	19.5886
295.998	14.1466	19.5839
297.999	15.3500	19.5795
300.001	16.5543	19.5753
301.999	17.7579	19.5713
304.001	18.9619	19.5674
306.002	20.1678	19.5635
308.002	21.3725	19.5598
309.999	22.5758	19.5560
311.999	23.7842	19.5524
315.999	26.1888	19.5452
319.999	28.6007	19.5380
324.002	30.9990	19.5310
327.999	33.3941	19.5241
290.000	4.9719	18.5482
291.000	5.4774	18.5450
292.000	5.9816	18.5414
293.001	6.4815	18.5373
294.001	6.9806	18.5322
296.001	7.9414	18.5141
297.999	8.9106	18.4966
299.999	9.9103	18.4880
302.000	10.9257	18.4818
303.998	11.9428	18.4767
306.000	12.9682	18.4721
308.000	13.9931	18.4678
310.000	15.0194	18.4638
312.002	16.0497	18.4599
316.000	18.1104	18.4526
320.000	20.1735	18.4454

Table 1. Compressed Gas and Liquid-Phase PVT Data for Fluoromethane (HFC-41) in SI Units (continued).

T	P	ρ
K	MPa	mol·dm ⁻³
323.999	22.2349	18.4385
328.000	24.2980	18.4318
332.000	26.3637	18.4251
336.002	28.4230	18.4186
340.000	30.4830	18.4121
344.002	32.5415	18.4056
348.000	34.5921	18.3992
300.001	4.7418	16.9472
300.999	5.1390	16.9447
302.000	5.5349	16.9420
303.000	5.9330	16.9390
304.001	6.3276	16.9358
306.001	7.1170	16.9274
308.000	7.8936	16.9120
310.002	8.6734	16.8959
312.000	9.4679	16.8874
314.000	10.2710	16.8815
315.999	11.0811	16.8766
317.999	11.8932	16.8723
319.999	12.7079	16.8682
324.001	14.3409	16.8609
328.001	15.9858	16.8541
331.999	17.6232	16.8488
336.000	19.2728	16.8425
340.000	20.9259	16.8363
344.002	22.5808	16.8302
348.001	24.2362	16.8242
352.000	25.8912	16.8183
356.000	27.5489	16.8124
360.000	29.2040	16.8065
363.999	30.8587	16.8007
367.999	32.5115	16.7949
372.000	34.1636	16.7890
310.000	5.1991	14.7286
310.999	5.4742	14.7266
311.998	5.7550	14.7244
313.000	6.0360	14.7221
314.000	6.3180	14.7196
316.001	6.8842	14.7137
318.002	7.4523	14.7052
320.000	8.0197	14.6916
322.001	8.5905	14.6798
324.001	9.1656	14.6729
327.998	10.3330	14.6641
332.001	11.5146	14.6568
336.000	12.7046	14.6504
340.000	13.9017	14.6443
343.999	15.1044	14.6386
347.999	16.3116	14.6331
352.001	17.5233	14.6277
356.001	18.7375	14.6224
360.001	19.9543	14.6172

Table 1. Compressed Gas and Liquid-Phase PVT Data for Fluoromethane (HFC-41) in SI Units (continued).

T	P	ρ
K	MPa	mol·dm ⁻³
363.999	21.1726	14.6120
368.000	22.3931	14.6069
372.002	23.6127	14.6019
376.002	24.8337	14.5968
380.001	26.0567	14.5917
384.000	27.2806	14.5867
387.998	28.5023	14.5817
392.002	29.7240	14.5767
396.000	30.9428	14.5717
399.998	32.1613	14.5666
319.998	6.8061	13.1154
321.000	7.0279	13.1128
322.001	7.2522	13.1095
322.998	7.4800	13.1055
323.999	7.7051	13.1005
325.999	8.1587	13.0886
327.998	8.6162	13.0796
330.000	9.0776	13.0735
332.000	9.5419	13.0688
334.002	10.0099	13.0648
335.999	10.4781	13.0613
340.001	11.4237	13.0550
344.000	12.3754	13.0493
347.999	13.3328	13.0440
351.998	14.2941	13.0389
356.000	15.2600	13.0340
360.001	16.2277	13.0292
364.001	17.1980	13.0245
368.002	18.1715	13.0199
372.000	19.1458	13.0153
376.000	20.1219	13.0107
379.999	21.0988	13.0062
384.000	22.0772	13.0017
387.999	23.0554	12.9972
391.999	24.0344	12.9927
395.999	25.0129	12.9883
399.999	25.9923	12.9838
320.001	6.3260	10.7655
320.998	6.4852	10.7642
321.998	6.6445	10.7627
323.001	6.8068	10.7609
323.999	6.9689	10.7589
326.000	7.2960	10.7540
328.000	7.6251	10.7474
330.000	7.9559	10.7387
332.002	8.2891	10.7305
335.999	8.9586	10.7194
339.999	9.6346	10.7122
343.999	10.3154	10.7065
348.000	10.9998	10.7015
351.998	11.6867	10.6969
356.001	12.3767	10.6925
360.002	13.0684	10.6883

Table 1. Compressed Gas and Liquid-Phase PVT Data for Fluoromethane (HFC-41) in SI Units (continued).

T	P	ρ
K	MPa	mol·dm ⁻³
363.999	13.7619	10.6842
368.002	14.4558	10.6802
372.000	15.1518	10.6764
376.001	15.8485	10.6725
379.998	16.5453	10.6687
383.999	17.2436	10.6650
388.000	17.9423	10.6612
392.001	18.6407	10.6575
395.999	19.3387	10.6538
399.999	20.0367	10.6502
320.002	6.2317	8.4227
321.999	6.4775	8.4206
324.000	6.7234	8.4182
326.000	6.9691	8.4154
327.999	7.2144	8.4120
330.000	7.4597	8.4077
332.000	7.7045	8.4021
336.001	8.1936	8.3891
339.999	8.6829	8.3796
344.001	9.1724	8.3731
347.999	9.6620	8.3681
352.000	10.1518	8.3637
356.000	10.6405	8.3590
360.000	11.1298	8.3555
364.001	11.6195	8.3521
367.999	12.1082	8.3488
371.998	12.5965	8.3456
376.001	13.0847	8.3425
380.000	13.5727	8.3394
384.002	14.0606	8.3364
388.002	14.5475	8.3334
392.002	15.0340	8.3304
396.000	15.5201	8.3275
399.998	16.0054	8.3245
319.999	6.0003	5.6781
321.998	6.1630	5.6768
323.999	6.3243	5.6753
325.999	6.4842	5.6738
328.000	6.6433	5.6723
330.000	6.8009	5.6708
331.999	6.9578	5.6690
335.998	7.2690	5.6646
340.001	7.5768	5.6589
343.999	7.8812	5.6512
347.999	8.1832	5.6432
351.999	8.4835	5.6368
355.999	8.7831	5.6319
360.002	9.0816	5.6278
364.001	9.3782	5.6244
367.999	9.6739	5.6213
372.000	9.9686	5.6185
376.000	10.2623	5.6159

Table 1. Compressed Gas and Liquid-Phase PVT Data for Fluoromethane (HFC-41) in SI Units (continued).

T	P	ρ
K	MPa	mol·dm ⁻³
380.001	10.5551	5.6133
384.001	10.8468	5.6109
388.001	11.1377	5.6086
392.000	11.4275	5.6063
396.000	11.7165	5.6041
399.999	12.0047	5.6019
320.002	4.9891	3.2387
322.001	5.0712	3.2380
323.998	5.1527	3.2373
326.000	5.2341	3.2366
328.001	5.3149	3.2359
330.000	5.3952	3.2352
332.000	5.4752	3.2344
336.000	5.6338	3.2329
340.000	5.7910	3.2314
344.001	5.9470	3.2298
348.002	6.1017	3.2282
352.000	6.2552	3.2265
356.000	6.4073	3.2248
360.000	6.5585	3.2230
364.002	6.7082	3.2211
368.002	6.8569	3.2191
372.000	7.0042	3.2169
376.000	7.1510	3.2146
379.998	7.2966	3.2120
384.000	7.4407	3.2091
387.999	7.5835	3.2059
392.001	7.7250	3.2022
396.002	7.8648	3.1982
400.000	8.0044	3.1941
319.999	4.0606	2.2369
322.001	4.1127	2.2365
324.000	4.1646	2.2360
326.000	4.2162	2.2356
327.998	4.2676	2.2352
329.998	4.3187	2.2348
331.998	4.3695	2.2343
336.000	4.4710	2.2335
340.001	4.5714	2.2326
344.000	4.6712	2.2317
348.000	4.7703	2.2308
352.001	4.8687	2.2299
356.001	4.9663	2.2290
360.000	5.0632	2.2281
364.001	5.1589	2.2271
368.001	5.2550	2.2262
372.001	5.3504	2.2252
376.001	5.4452	2.2242
380.000	5.5397	2.2233
384.000	5.6336	2.2223
388.000	5.7272	2.2212
392.000	5.8203	2.2202

Table 1. Compressed Gas and Liquid-Phase PVT Data for Fluoromethane (HFC-41) in SI Units (continued).

T	P	ρ
K	MPa	mol·dm ⁻³
395.999	5.9130	2.2191
400.000	6.0051	2.2181
320.000	2.8997	1.3850
321.999	2.9290	1.3848
323.999	2.9581	1.3846
326.000	2.9871	1.3843
327.999	3.0160	1.3841
330.000	3.0448	1.3839
332.000	3.0736	1.3836
336.000	3.1307	1.3831
340.000	3.1875	1.3827
343.999	3.2440	1.3822
348.000	3.3002	1.3817
351.998	3.3560	1.3812
355.999	3.4116	1.3807
359.999	3.4668	1.3802
363.998	3.5221	1.3797
368.000	3.5769	1.3792
371.998	3.6315	1.3787
376.000	3.6858	1.3782
379.998	3.7399	1.3777
383.998	3.7939	1.3772
388.001	3.8476	1.3767
392.001	3.9011	1.3761
395.998	3.9544	1.3756
399.999	4.0076	1.3751

Table 2. Compressed Gas and Liquid-Phase PVT Data for Fluoromethane (HFC-41) in PI Units.

T °F	P psia	ρ lb·ft ⁻³
-222.07	550.375	62.911
-220.27	865.543	62.889
-218.47	1116.567	62.848
-216.67	1345.750	62.793
-214.87	1658.669	62.770
-213.07	1996.785	62.755
-211.27	2345.957	62.742
-209.47	2698.718	62.731
-207.67	3052.959	62.721
-205.87	3409.288	62.711
-204.07	3765.100	62.702
-202.27	4120.449	62.693
-200.47	4477.122	62.685
-198.67	4831.722	62.676
-204.07	553.543	61.742
-202.27	847.515	61.721
-200.47	1093.617	61.686
-198.67	1301.970	61.630
-196.87	1583.224	61.605
-195.07	1893.551	61.590
-193.27	2213.810	61.577
-191.47	2539.102	61.566
-189.67	2865.468	61.556
-187.87	3192.790	61.547
-186.07	3522.410	61.538
-184.27	3849.708	61.529
-182.47	4177.300	61.521
-180.67	4506.369	61.513
-178.87	4832.846	61.505
-182.47	558.899	60.325
-180.67	829.535	60.306
-178.87	1064.970	60.276
-177.07	1256.722	60.220
-175.27	1505.088	60.193
-173.47	1783.669	60.177
-171.67	2074.080	60.164
-169.87	2366.934	60.154
-168.07	2662.686	60.144
-166.27	2960.568	60.135
-164.47	3256.703	60.126
-162.67	3556.171	60.118
-160.87	3852.697	60.110
-159.07	4149.043	60.103
-157.27	4446.879	60.095
-155.47	4742.536	60.088
-153.67	5039.841	60.080
-157.27	558.142	58.638
-155.47	801.934	58.622
-153.67	1026.052	58.597
-151.87	1203.952	58.545
-150.07	1416.852	58.513
-148.27	1662.386	58.496
-146.47	1917.748	58.484
-144.67	2179.083	58.473

Table 2. Compressed Gas and Liquid-Phase PVT Data for Fluoromethane (HFC-41) in PI Units (continued).

T °F	P psia	ρ lb·ft ⁻³
-142.87	2442.689	58.463
-141.07	2706.589	58.455
-139.27	2972.553	58.446
-137.47	3237.253	58.438
-135.67	3502.872	58.431
-133.87	3767.721	58.424
-132.07	4032.203	58.416
-130.27	4297.442	58.409
-128.47	4561.478	58.402
-126.67	4825.364	58.396
-124.87	5088.994	58.389
-128.47	553.926	56.664
-126.67	770.960	56.650
-124.87	978.137	56.629
-123.07	1148.457	56.589
-121.27	1325.918	56.547
-119.47	1535.743	56.528
-117.67	1758.726	56.515
-115.87	1986.280	56.505
-114.07	2215.222	56.495
-112.27	2447.186	56.487
-110.47	2678.304	56.479
-108.67	2910.530	56.471
-106.87	3142.607	56.464
-105.07	3374.579	56.457
-103.27	3607.855	56.450
-101.47	3839.632	56.443
-99.67	4071.906	56.437
-97.87	4303.031	56.431
-96.07	4533.918	56.424
-94.27	4765.206	56.418
-92.47	4995.246	56.412
-99.67	549.462	54.616
-97.87	745.705	54.603
-96.07	933.002	54.586
-94.27	1099.326	54.557
-92.47	1249.410	54.510
-90.67	1428.011	54.488
-88.87	1619.807	54.474
-87.07	1817.189	54.463
-85.27	2017.360	54.454
-83.47	2217.957	54.445
-81.67	2420.865	54.437
-78.07	2826.100	54.423
-74.47	3231.088	54.410
-70.87	3637.720	54.397
-67.27	4041.976	54.385
-63.67	4444.451	54.373
-60.07	4846.866	54.362
-63.67	527.171	51.887
-61.87	690.064	51.876
-60.07	853.256	51.862
-58.27	1006.712	51.844

Table 2. Compressed Gas and Liquid-Phase PVT Data for Fluoromethane
(HFC-41) in PI Units (continued).

T °F	P psia	ρ lb·ft ⁻³
-56.47	1143.517	51.809
-54.67	1280.541	51.772
-52.87	1436.264	51.754
-51.07	1598.688	51.742
-49.27	1764.276	51.732
-47.47	1931.947	51.723
-45.67	2099.650	51.716
-42.07	2437.372	51.702
-38.47	2776.296	51.689
-34.87	3115.005	51.677
-31.27	3453.699	51.666
-27.67	3791.084	51.655
-24.07	4127.528	51.644
-20.47	4463.928	51.634
-16.87	4799.022	51.623
-13.27	5134.599	51.613
-27.67	551.186	48.942
-25.87	688.585	48.932
-24.07	823.817	48.921
-22.27	956.544	48.907
-20.47	1080.284	48.885
-18.67	1195.303	48.846
-16.87	1319.118	48.821
-15.07	1451.444	48.807
-13.27	1586.435	48.797
-11.47	1723.580	48.788
-9.67	1861.816	48.780
-6.07	2140.569	48.767
-2.47	2418.898	48.755
1.13	2697.027	48.743
4.73	2976.371	48.733
8.33	3255.460	48.722
11.93	3533.957	48.712
15.53	3812.284	48.702
19.13	4090.488	48.693
22.73	4368.389	48.683
26.33	4645.375	48.674
29.93	4921.489	48.665
8.33	555.561	45.566
10.13	666.024	45.558
11.93	776.149	45.549
13.73	885.822	45.539
15.53	992.056	45.525
17.33	1093.596	45.504
19.13	1191.183	45.471
20.93	1292.747	45.448
22.73	1399.605	45.435
24.53	1508.186	45.425
26.33	1618.635	45.416
29.93	1840.498	45.403
33.53	2062.816	45.391
37.13	2285.974	45.380
40.73	2509.637	45.370

Table 2. Compressed Gas and Liquid-Phase PVT Data for Fluoromethane (HFC-41) in PI Units (continued).

T °F	P psia	ρ lb-ft ⁻³
44.33	2733.708	45.360
47.93	2957.494	45.350
51.53	3181.488	45.341
55.13	3405.236	45.332
58.73	3628.443	45.324
62.33	3851.505	45.315
65.93	4074.708	45.306
69.53	4296.970	45.298
73.13	4518.829	45.290
76.73	4741.000	45.281
80.33	4962.575	45.273
44.33	695.890	41.779
46.13	782.672	41.771
47.93	867.842	41.763
49.73	952.804	41.753
51.53	1035.972	41.739
55.13	1195.907	41.690
58.73	1361.427	41.659
62.33	1532.278	41.642
65.93	1705.289	41.629
69.53	1878.625	41.618
73.13	2051.795	41.608
76.73	2226.332	41.599
80.33	2400.998	41.590
83.93	2575.568	41.582
87.53	2750.192	41.573
91.13	2925.094	41.565
94.73	3099.814	41.557
98.33	3274.339	41.549
101.93	3449.601	41.541
109.13	3798.358	41.526
116.33	4148.183	41.511
123.53	4496.021	41.496
130.73	4843.396	41.481
62.33	721.117	39.408
64.13	794.427	39.401
65.93	867.556	39.394
67.73	940.057	39.385
69.53	1012.447	39.374
73.13	1151.803	39.336
76.73	1292.377	39.298
80.33	1437.372	39.280
83.93	1584.646	39.267
87.53	1732.163	39.256
91.13	1880.872	39.246
94.73	2029.527	39.237
98.33	2178.381	39.229
101.93	2327.813	39.220
109.13	2626.692	39.205
116.33	2925.917	39.189
123.53	3224.893	39.175
130.73	3524.127	39.161

Table 2. Compressed Gas and Liquid-Phase PVT Data for Fluoromethane (HFC-41) in PI Units (continued).

T °F	P psia	ρ lb-ft ⁻³
137.93	3823.729	39.146
145.13	4122.411	39.133
152.33	4421.187	39.119
159.53	4719.743	39.105
166.73	5017.163	39.091
80.33	687.737	36.006
82.13	745.351	36.001
83.93	802.773	35.995
85.73	860.502	35.989
87.53	917.743	35.982
91.13	1032.229	35.964
94.73	1144.874	35.932
98.33	1257.971	35.898
101.93	1373.201	35.879
105.53	1489.682	35.867
109.13	1607.173	35.856
112.73	1724.959	35.847
116.33	1843.130	35.839
123.53	2079.977	35.823
130.73	2318.547	35.809
137.93	2556.033	35.797
145.13	2795.288	35.784
152.33	3035.044	35.771
159.53	3275.067	35.758
166.73	3515.169	35.745
173.93	3755.203	35.733
181.13	3995.625	35.720
188.33	4235.677	35.708
195.53	4475.682	35.695
202.73	4715.400	35.683
209.93	4955.011	35.670
98.33	754.065	31.293
100.13	793.968	31.288
101.93	834.699	31.284
103.73	875.451	31.279
105.53	916.353	31.274
109.13	998.468	31.261
112.73	1080.867	31.243
116.33	1163.155	31.214
119.93	1245.951	31.189
123.53	1329.359	31.174
130.73	1498.679	31.156
137.93	1670.050	31.140
145.13	1842.640	31.127
152.33	2016.275	31.114
159.53	2190.710	31.102
166.73	2365.801	31.090
173.93	2541.542	31.078
181.13	2717.651	31.067
188.33	2894.126	31.056
195.53	3070.832	31.045
202.73	3247.850	31.034
209.93	3424.726	31.023

Table 2. Compressed Gas and Liquid-Phase PVT Data for Fluoromethane (HFC-41) in PI Units (continued).

T °F	p psia	ρ lb·ft ⁻³
217.13	3601.823	31.013
224.33	3779.202	31.002
231.53	3956.710	30.991
238.73	4133.912	30.981
245.93	4311.101	30.970
253.13	4487.867	30.959
260.33	4664.605	30.949
116.33	987.147	27.865
118.13	1019.309	27.860
119.93	1051.846	27.853
121.73	1084.877	27.844
123.53	1117.530	27.834
127.13	1183.318	27.808
130.73	1249.680	27.789
134.33	1316.591	27.776
137.93	1383.938	27.766
141.53	1451.820	27.758
145.13	1519.717	27.750
152.33	1656.861	27.737
159.53	1794.901	27.725
166.73	1933.766	27.714
173.93	2073.178	27.703
181.13	2213.281	27.692
188.33	2353.634	27.682
195.53	2494.361	27.672
202.73	2635.554	27.662
209.93	2776.857	27.653
217.13	2918.437	27.643
224.33	3060.126	27.633
231.53	3202.028	27.624
238.73	3343.901	27.614
245.93	3485.897	27.605
253.13	3627.809	27.595
260.33	3769.865	27.586
116.33	917.501	22.873
118.13	940.593	22.870
119.93	963.710	22.867
121.73	987.243	22.863
123.53	1010.753	22.859
127.13	1058.188	22.848
130.73	1105.920	22.834
134.33	1153.907	22.816
137.93	1202.233	22.798
145.13	1299.342	22.775
152.33	1397.373	22.759
159.53	1496.118	22.747
166.73	1595.384	22.737
173.93	1695.006	22.727
181.13	1795.094	22.717
188.33	1895.415	22.709
195.53	1995.994	22.700
202.73	2096.635	22.692
209.93	2197.581	22.683
217.13	2298.637	22.675

Table 2. Compressed Gas and Liquid-Phase PVT Data for Fluoromethane (HFC-41) in PI Units (continued).

T °F	P psia	ρ lb-ft ⁻³
224.33	2399.695	22.667
231.53	2500.976	22.659
238.73	2602.310	22.651
245.93	2703.600	22.643
253.13	2804.846	22.635
260.33	2906.081	22.628
116.33	903.834	17.895
119.93	939.476	17.891
123.53	975.144	17.885
127.13	1010.786	17.880
130.73	1046.361	17.872
134.33	1081.943	17.863
137.93	1117.446	17.851
145.13	1188.387	17.824
152.33	1259.347	17.803
159.53	1330.340	17.790
166.73	1401.356	17.779
173.93	1472.391	17.770
181.13	1543.279	17.760
188.33	1614.246	17.752
195.53	1685.268	17.745
202.73	1756.140	17.738
209.93	1826.969	17.731
217.13	1897.769	17.725
224.33	1968.552	17.718
231.53	2039.321	17.712
238.73	2109.932	17.705
245.93	2180.492	17.699
253.13	2251.001	17.693
260.33	2321.385	17.686
116.33	870.271	12.064
119.93	893.866	12.061
123.53	917.261	12.058
127.13	940.448	12.055
130.73	963.533	12.052
134.33	986.384	12.048
137.93	1009.137	12.045
145.13	1054.273	12.035
152.33	1098.918	12.023
159.53	1143.068	12.007
166.73	1186.875	11.990
173.93	1230.434	11.976
181.13	1273.878	11.966
188.33	1317.171	11.957
195.53	1360.191	11.950
202.73	1403.083	11.943
209.93	1445.829	11.937
217.13	1488.425	11.932
224.33	1530.889	11.926
231.53	1573.201	11.921
238.73	1615.392	11.916
245.93	1657.420	11.911
253.13	1699.341	11.907

Table 2. Compressed Gas and Liquid-Phase PVT Data for Fluoromethane (HFC-41) in PI Units (continued).

T °F	P psia	ρ lb·ft ⁻³
260.33	1741.138	11.902
116.33	723.611	6.881
119.93	735.513	6.880
123.53	747.340	6.878
127.13	759.137	6.877
130.73	770.856	6.875
134.33	782.514	6.873
137.93	794.113	6.872
145.13	817.106	6.869
152.33	839.920	6.866
159.53	862.538	6.862
166.73	884.972	6.859
173.93	907.238	6.855
181.13	929.305	6.851
188.33	951.223	6.848
195.53	972.942	6.844
202.73	994.503	6.839
209.93	1015.874	6.835
217.13	1037.166	6.830
224.33	1058.289	6.824
231.53	1079.189	6.818
238.73	1099.886	6.811
245.93	1120.412	6.803
253.13	1140.700	6.795
260.33	1160.936	6.786
116.33	588.937	4.753
119.93	596.489	4.752
123.53	604.018	4.751
127.13	611.505	4.750
130.73	618.965	4.749
134.33	626.373	4.748
137.93	633.743	4.747
145.13	648.456	4.745
152.33	663.032	4.743
159.53	677.507	4.742
166.73	691.870	4.740
173.93	706.143	4.738
181.13	720.299	4.736
188.33	734.354	4.734
195.53	748.242	4.732
202.73	762.173	4.730
209.93	776.007	4.728
217.13	789.759	4.726
224.33	803.470	4.724
231.53	817.087	4.721
238.73	830.655	4.719
245.93	844.161	4.717
253.13	857.602	4.715
260.33	870.965	4.713
116.33	420.563	2.943
119.93	424.808	2.942
123.53	429.035	2.942
127.13	433.237	2.941

Table 2. Compressed Gas and Liquid-Phase PVT Data for Fluoromethane (HFC-41) in PI Units (continued).

T	P	ρ
$^{\circ}\text{F}$	psia	$\text{lb}\cdot\text{ft}^{-3}$
130.73	437.440	2.941
134.33	441.605	2.940
137.93	445.782	2.940
145.13	454.072	2.939
152.33	462.308	2.938
159.53	470.498	2.937
166.73	478.647	2.936
173.93	486.748	2.935
181.13	494.804	2.933
188.33	502.822	2.932
195.53	510.838	2.931
202.73	518.790	2.930
209.93	526.699	2.929
217.13	534.585	2.928
224.33	542.432	2.927
231.53	550.254	2.926
238.73	558.045	2.925
245.93	565.813	2.924
253.13	573.541	2.923
260.33	581.249	2.922

Table 3. Vapor Pressure Measurements for Fluoromethane (HFC-41) in SI Units.

T	P
K	kPa
132.00	0.5785
136.00	0.8884
140.00	1.3645
145.00	2.2990
150.00	3.7764
155.00	6.0830
160.00	9.3391
165.00	14.073
170.00	20.646
175.00	29.642
180.00	41.581
185.00	57.194
190.00	77.194
195.00	102.31
200.00	133.48
205.00	171.94
210.00	218.55
215.00	274.36
220.00	340.27
225.00	418.62
230.00	509.25
235.00	614.79
240.00	735.45
245.00	873.79
250.00	1030.05
255.00	1207.40
260.00	1405.72
265.00	1627.97
270.00	1875.91
275.00	2150.16
280.00	2454.22
285.00	2788.50
290.00	3157.08
295.00	3561.41
300.00	4005.46
305.00	4490.47
310.00	5022.12
315.00	5605.92
317.00	5861.66

Table 4. Vapor Pressure Measurements for Fluoromethane (HFC-41) in PI Units.

T	P
°F	psia
-222.07	0.0839
-214.87	0.1288
-207.67	0.1979
-198.67	0.3334
-189.67	0.5477
-180.67	0.8823
-171.67	1.3545
-162.67	2.0411
-153.67	2.9944
-144.67	4.2992
-135.67	6.0308
-126.67	8.2953
-117.67	11.196
-108.67	14.839
-99.67	19.360
-90.67	24.938
-81.67	31.698
-72.67	39.793
-63.67	49.352
-54.67	60.716
-45.67	73.860
-36.67	89.168
-27.67	106.67
-18.67	126.73
-9.67	149.40
-0.67	175.12
8.33	203.88
17.33	236.12
26.33	272.08
35.33	311.85
44.33	355.95
53.33	404.44
62.33	457.90
71.33	516.54
80.33	580.94
89.33	651.29
98.33	728.40
107.33	813.07
110.93	850.16