THERMOPHYSICAL PROPERTIES OF HCFC ALTERNATIVES

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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) performance tests and calibrations for new vapor-liquid equilibrium apparatus that will provide improved, state-of-the-art accuracy in temperature and composition determination,

(b) isochoric PVT measurements on HFC-41 (fluoromethane) from 132 to 328 K (-222 to 131°F) up to 35 MPa (5100 psia), (c) preparation of an equimolar mixture of R41/744, and (d) preparation and performance testing of a new spherical resonator for sound speed measurements over a wide range of temperatures for HFC-41. A summary of related work supported by the Department of Energy is presented.

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)

In the last progress report we presented a detailed analysis of vapor-liquid equilibrium (VLE) and density data taken on the existing VLE apparatus which employs an air-bath thermostat (oven) for the temperature-controlled environment. As part of the data evaluation, we compared our data to all available data to examine the data for consistency and agreement with other laboratories. The data comparisons revealed considerable scatter for most of the sources, both large scatter within the data of a given laboratory and scatter between the data of different laboratories. This led to a series of performance tests on the VLE apparatus to assess the effects of adsorption, of heats of vaporization, of phase envelope widths, and of the slopes of the density versus temperature curves on the quality of measurements. Since the existing VLE apparatus had been previously used for measurements on hydrocarbons, an analysis of the differences involved with measurements on refrigerants was carried out. This analysis showed that measurements on refrigerants were more sensitive to temperature gradients than for hydrocarbons, and it was obvious that other researchers had encountered the same problems.

The existing VLE apparatus with the air-bath thermostat had been pushed to the limit in an effort to minimize temperature gradients. This limit was not sufficient to meet our goals for the accuracy of VLE measurements for refrigerant mixtures. Thus, it was essential to carry out any future VLE measurements on the new apparatus that employs a liquid-bath thermostat. The use of this apparatus is expected to provide greatly improved (state-of-the-art) measurements on refrigerant mixtures, since the temperature gradients have been significantly reduced using a liquid-bath instead of an air-bath thermostat.

Most of the past quarter has been devoted to the preparation of this new apparatus for measurements. Comprehensive performance tests for temperature gradients and stability have been accomplished. The densimeter and pressure transducers are being carefully calibrated over the desired operating ranges. The calibrations should be completed next week, and measurements will be first made at low temperatures on systems previously investigated with the air-bath apparatus. It is expected that these new measurements will be state of the art exhibiting small internal scatter and can be used to resolve discrepancies between data from independent research laboratories.

As mentioned above, because of the potential problems resulting from temperature gradients, the new VLE apparatus has been tested for temperature gradients and temperature stability. A standard 25 Ω platinum resistance thermometer (PRT) was moved to different locations inside the dewar to measure temperature gradients within the temperature-controlled environment. The gradients were measured at -50°C (-58°F), -10°C (14°F), 50°C (122°F), and 150°C (302°F). In all cases, the variation of the measured temperatures within the region where the main cell, densimeters, and recirculation pumps are located was within

the uncertainty [± 10 mK ($\pm 0.02^\circ\text{F}$)] of the PRT. When the PRT was moved into the heating and cooling coils at the bottom of the dewar, temperature variations of 10 to 20 mK (0.02 to 0.04°F) were observed. When the PRT was moved within 4.5 cm (1.8 in) of the surface of the oil, temperature gradients of 10 to 20 mK (0.02 to 0.04°F) were observed. Small cartridge heaters were mounted in the head space of the dewar to reduce these gradients at the higher temperatures. All lines and valves outside of the dewar are heat traced to maintain the temperature of the pressure measuring system well above the temperature of the main part of the system. This ensures that only vapor is in the lines outside of the system, thus eliminating the possibilities of liquid head effects on the pressure measurement.

The three 100 Ω PRTs that will be used were calibrated and tested for repeatability, stability, and accuracy. These tests ensure that all potential sources of uncertainty associated with the temperature measurements, such as PRT drifts, multimeter drifts, and power fluctuations of the electrical system in the building are taken into account, and not just the uncertainties of the PRTs alone. These tests were performed by placing two additional, standard reference quality 25 Ω PRTs in the dewar. The system was maintained at a selected temperature for several hours with temperature measurements being recorded by all 5 PRTs at 30 minute intervals. This procedure was repeated at numerous temperatures between -50 and 150°C (-58 to 302°F). The two 25 Ω PRTs and the main bath 100 Ω PRT had an estimated uncertainty of ± 0.008 K ($\pm 0.014^\circ\text{F}$) and a maximum uncertainty of ± 0.015 K ($\pm 0.027^\circ\text{F}$). The other two 100 Ω PRTs, which are used only to indicate temperature changes, are of lower quality and show deviations approximately twice as large as the standard PRTs. The scatter was evenly distributed with no indication of a systematic temperature trend.

The temperature stability of the new apparatus is ± 0.001 K ($\pm 0.0018^\circ\text{F}$) over a 15 minute period when controlled with a heating rate adjusted to balance the heat loss. At a result of room temperature variations, the system temperature was observed to change by as much as ± 0.3 K ($\pm 0.54^\circ\text{F}$) over a 12 h period when a constant heating rate was applied. A programmable power supply and proportional-integral-derivative control algorithm have been added to achieve temperature stability of ± 10 mK ($\pm 0.02^\circ\text{F}$) over extended periods of time.

Because temperature gradients result in conditions that are conducive to create pockets of material at different compositions at hot or cold spots in the sample lines (as occurred with the vapor gas chromatograph (GC) valve in the air-bath VLE apparatus), the sampling will be performed in a different manner. The volumes of the lines between the pumps and the main cell have been minimized. In the air-bath VLE apparatus the GC valves were part of the recirculation loops and were located in regions where hot or cold spots could exist. In the new VLE apparatus the GC valves will be located outside the system and connected by capillary lines to the upstream sides of the recirculation pumps. Capillary sampling is based on the plug flow nature of the material flowing out of the system through the capillary line. This means that there is no backmixing in the line. The disadvantage of capillary sampling is that it requires more material to make a composition analysis because it requires that the capillary lines are purged before each new sample is withdrawn. The advantage is that it can sample directly from the main cell or at a short distance away from the main cell and will not be affected by changing temperature gradients in the capillary line. This method of sampling has been used successfully in the cryogenic VLE apparatus at our laboratory and in other VLE apparatus for other temperature ranges at other laboratories.

We have attempted to anticipate any potential problems that the temperature gradient sensitivity of the refrigerant mixtures could cause. The significant reduction in the temperature gradients and the significant increase in the temperature stability will result in significantly improved accuracy of the density measurements. The density data for the new

system will be taken at saturation conditions rather than near saturation. Since the problems with temperature gradients have been eliminated, this means that large adjustments will not have to be made to the new data to provide densities at the coexistence boundary. We have also changed the densimeter calibration procedure in order to increase the accuracy of the density measurements.

The vibrating densimeters determine density by measuring the resonant frequency of vibration of a fluid-filled U-shaped tube. While this technique is very precise, it is not an absolute method, and the accuracy of the results is only as good as the calibration. The standard vibrating tube densimeter calibration uses only nitrogen and water as calibration fluids. We have expanded the standard calibration to include nitrogen, propane, and HFC-152a to cover the full range of temperatures, pressures, and densities anticipated in the upcoming refrigerant measurements. The temperature dependence of the frequencies of the densimeters are determined under vacuum at temperatures from -50 to 150°C (-58 to 302°F). Then the frequencies are determined as a function of pressure for nitrogen over the same temperature range. Next, the frequencies are measured as a function of pressure for water at temperatures above 0°C (32°F). Because the new apparatus has a low temperature limit of -50°C (-58°F) which is below the freezing point of water, R152a (with a comparable density to that of water) was used as a calibration fluid below 0°C (32°F). We have also added R290 (propane) as a calibration fluid since the densities of propane fall between those of water and nitrogen. For R290, water, nitrogen, and R152a, frequencies were recorded at pressures of 0.689, 1.724, 3.447, and 6.894 MPa (100, 250, 500, and 1000 psia) for each of the 3 to 10 temperatures. A total of 32 water state points, 44 nitrogen state points, 12 HFC-152a state points, 27 R290 state points, and 20 vacuum points were taken for each densimeter for calibration purposes. Figure 1 shows a plot of the calibration data for the liquid densimeter.

In the standard calibration procedure, the densimeters are calibrated over the full range of densities with an equal statistical weight on all of the data. Since we have one densimeter that is dedicated to liquid phase measurements and one densimeter that is dedicated to vapor phase measurements, the standard procedure can be modified to increase the accuracy of each densimeter in its density range. We will weight the propane and nitrogen data more heavily in the fit of the calibration data for the vapor densimeter, and the water, R152a, and propane data more heavily in the liquid densimeter calibrations. This should improve the overall accuracy of the density measurements to, at least, $\pm 0.0005 \text{ g/cm}^3$ ($\pm 0.032 \text{ lb/ft}^3$). The final part of the densimeter calibration depends on the pressure transducer calibrations.

Experience with the oscillating quartz crystal pressure transducers of the type used in the new VLE apparatus have shown them to be very good, except that the zero point can drift, and the factory calibrations are not always reliable. Thus, we have calibrated the pressure transducers using an oil dead weight gauge with an uncertainty of 0.01% and have incorporated a procedure that corrects for the zero point offset. The air-bath VLE apparatus was designed to be able to test the zero offset while in operation, and the new apparatus has the same capability. The oil dead weight gauge is being used to calibrate the three pressure transducers over their entire ranges of operation of 0 to 41.4 MPa (0 to 6000 psia), 0 to 6.9 MPa (0 to 1000 psia), and 0 to 1.38 MPa (0 - 200 psia).

As mentioned above, once the calibrations are completed, combined VLE and density measurements will be restarted on the binary mixtures, beginning with the R32/134a system. We will repeat our three lowest temperature isotherms, some isotherms from Higashi [Iwaki Meisei University, private communication], and some isotherms of Widiatmo *et al.*, [Widiatmo, J.V., Sato, H., and Watanabe, K., *Fluid Phase Equilibria* 99:199 (1994)]. We will also repeat two compositions on the higher temperature isotherms we measured. The data will be

compared to REFPROP to analyze the data for scatter and to compare it with the data from independent sources. Then we will proceed to the other binary mixtures and repeat measurements as needed.

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

Measurements on the equimolar ternary mixture of R32/134a/125 will be repeated using the same standard mixture that was used previously. These data will be compared with results from other laboratories to analyze the performance of the new system. A full range of measurements will be made on this system.

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

An equimolar mixture of R41/744 has been prepared using research grade pure components. More than 600 g (1.3 lb) of the mixture sample were prepared in a 16 L (0.57 ft³) cylinder. The balance used for preparing the sample has a resolution of 10⁻³ g (2.2x10⁻⁶ lb), which results in an uncertainty in the mole fraction of 10⁻⁵. This mixture will be used for isochoric PVT measurements at temperatures from approximately 220 to 400 K (-64 to 260°F). VLE measurements will be carried out on this system using the new liquid-bath VLE apparatus and a cryogenic VLE apparatus.

This system will be run in the new VLE apparatus at temperatures from the freezing point of CO₂ [-57°C (-71°F)] to the critical line. Densities can only be measured from -50°C (-58°F) to the critical line because of the low temperature limit of the densimeters.

Comprehensive data for the R143a/125 mixture

Comprehensive PVT measurements were completed and reported for an equimolar R143a/125 mixture during the previous quarter. C_v measurements will be initiated during the next quarter for this mixture.

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

Isochoric PVT measurements have been initiated for fluoromethane (HFC-41) on samples from a specially purified supply which contains no detectable amounts of diethyl ether, light organic, or halocarbon impurities, as determined by our gas chromatography/mass spectrometry analysis. Thus far, densities have been measured with an isochoric PVT apparatus at 194 points in the temperature range from 132 to 328 K (-222 to 131°F) with pressures up to 35 MPa (5100 psia). The lowest reported temperature is slightly above the published freezing point temperature of 131.4 K (-223°F). The measurements were carried out on a total of 10 runs at different filling densities. These data are in the dense liquid phase. The pressures, temperatures, and densities are presented in Tables 1 and 2, and the locations of the measurements are shown in Figure 2. During the next reporting period, saturated liquid densities will be determined for each isochore from its extrapolated intersection with

the vapor pressure curve. Also in the next period, further PVT measurements will be carried out for HFC-41 in the compressed gaseous region at temperatures as high as 400 K (260°F).

A new spherical resonator that will be used for sound speed measurements on HFC-41 is in the final stages of development. It is currently undergoing performance tests using argon gas, which will be used to determine the radius of the sphere. The temperature control system is being fine-tuned; this apparatus can be used for sound speed measurements over a range of, at least, -50 to 100°C (-58 to 212°F). These data will be used to calculate ideal gas heat capacities and second virial coefficients for HFC-41.

RELATED WORK

For several years, NIST has been conducting research on safe alternatives to the CFC and HCFC refrigerants for the Refrigeration Systems Program of the U.S. Department of Energy. The objective of this work is to provide the air conditioning and refrigeration industries with the fundamental data needed to accelerate the introduction of highly efficient, environmentally benign alternative refrigerants in response to the Montreal Protocol and the Clean Air Act, which regulate the CFC and HCFC refrigerants now in use. It is, thus, directly related to the ARTI work.

The research program currently underway includes two major research areas:

1. Thermodynamic performance of alternative refrigerants.
2. Thermophysical properties research.

The primary objective of the properties work is to develop new and highly advanced thermophysical properties models for incorporation into the REFPROP computer package, distributed by NIST. These models are required by industry to evaluate alternative working fluids as potential CFC and HCFC substitutes in air conditioning and refrigeration applications and for equipment design. Tasks in support of this modeling work involve experimental mixture measurements which are complementary to the ARTI work. The research on "Thermodynamic performance of alternative refrigerants" is being carried out in the Building and Fire Research Laboratory of NIST.

Thermophysical property measurements on CFC alternatives

Comprehensive isochoric PVT measurements have been carried out on R32/134a, R32/125, and R125/134a mixtures. VLE properties for the R32/134a and R32/125 systems were measured. As for the work supported by ARTI, the lower temperature isotherms will be repeated for these systems in the new liquid-bath VLE apparatus. Heat capacity at constant volume (C_v) data have been obtained for the R32/134a system. C_v measurements are underway for the R32/125 system to be followed by measurements on the R125/134a system. Other tasks to be carried out in the next two years include: (1) thermal conductivity and viscosity measurements on refrigerant mixtures (R32/134a, R125/134a, R32/290, R290/134a, and R32/125/134a), (b) thermodynamic (PVT and C_v) and transport (viscosity and thermal conductivity) properties of ammonia, (c) comprehensive PVT and C_v measurements for two compositions of the R32/125/134a mixtures, and (d) comprehensive PVT, C_v , and VLE measurements on hydrocarbon mixtures (R290/600a).

Comparisons of data through IEA (International Energy Agency) Annex 18

A development from the AREP (Alternative Refrigerants Evaluation Program, organized by ARI) meeting held June 23, 1995 in San Diego was the decision by ARI to try to conduct the data gathering efforts that they were planning among the chemical companies through IEA Annex 18. The chemical companies in attendance at the meeting (DuPont, AlliedSignal, ICI, Atochem) indicated their willingness to join the Annex. This decision has been reconfirmed. ICI actually has already joined. A meeting with these companies will take place October 25, 1995 in Washington, DC to acquaint the companies with Annex tasks and procedures.

In spite of (or maybe because of) the emergence of various packages from the chemical companies, there was a consensus at AREP to give the task of generating property data to an impartial third party (NIST) and to arrive at a set of properties that the industry can standardize upon. Toward this end, ARI was trying to get the chemical companies to submit their data to NIST, so that we could use them to improve the numbers from REFPROP; this will now occur through the Annex 18. The mixture data measured under ARTI and DoE support have been submitted to the Annex comparisons and constitute a major portion of the database, including the majority of the heat capacity data.

Mixture examples and recommendation

A prime feature of REFPROP has always been its applicability to mixtures. In this section the properties calculated with REFPROP are compared with measured data for two representative mixtures using both the Carnahan-Starling-DeSantis (CSD) equation of state and the extended corresponding states (ECS) model.

Mixture calculations may be carried out with the CSD model or the ECS model. The user also has the choice of using mixture interaction parameters generated by the program or inputting his or her own values. We recommend that the values generated by REFPROP be used in most cases. For more than 60 binary pairs, these values are based on experimental data. The CSD model has one temperature-dependent interaction parameter. For pairs without experimental information, the CSD interaction parameter is estimated using the algorithm of Morrison and McLinden (1993). The ECS model option uses three interaction parameters, one for phase equilibria and the remaining two for single-phase properties. The phase equilibria interaction parameter is the same one used for the Peng-Robinson (1976) equation of state. In cases where the user has access to proprietary mixture data, they may wish to input their own interaction parameter values. (It is important to note that interaction parameters are specific for a given model and are not interchangeable among different models; although the interaction parameters for many equations of state have similar interpretations, the numerical values are usually different.)

Figures 3-7 present comparisons between experimental mixture data and values calculated with REFPROP using both the ECS and CSD models.

The first comparisons, Figures 3-4, are for bubble point pressures (the pressure of a liquid in equilibrium with vapor). Interaction parameters are most often calculated from bubble point pressures for several reasons: bubble point pressures are quite sensitive to variations in the value of the interaction parameter, bubble pressures are important in refrigeration calculations, azeotropes are most easily detected from bubble pressure data, but, out of necessity, the most important reason is that often bubble pressures are the only data

available for many mixtures. All of the mixture comparisons show similar agreement: the CSD and the ECS models reproduce the experimental bubble pressure data to approximately 1-2 %. Figures 3a and 3b show the mixture R32/R134a; Figures 4a and 4b show the mixture R32/R125. Both models represent the data well, but with subtle differences. The ECS model shows a slight systematic deviation with temperature for R32/R134a (Figure 3a). The temperature-dependent interaction parameter in the CSD model allows it to reproduce the data within its experimental scatter. For the R32/R125 mixture, the ECS model reproduces the data within its experimental scatter (Figure 4a), while the CSD model shows a slight systematic variation with composition.

Figures 5a and 5b show comparisons between experimental liquid phase isochoric heat capacity data and the model predictions for the system R32/R134a at approximately 50% R32 (molar basis). For this property, the ECS model performs significantly better than the CSD: For this mixture the CSD model tends to overpredict the isochoric heat capacity by 25-38%. The ECS model has percentage deviations ranging from -12 to +1% for this property.

The final four figures, Figures 6a,b and 7a,b show comparisons of single phase PVT (density) data with the model predictions. Figures 6a and 6b show the mixture R32/R134a, and Figures 7a and 7b show the R32/R125 system. For both mixtures, the ECS model performs significantly better than the CSD for compressed liquid densities.

Recommendations. Although the performance of both models for phase equilibria is comparable, the ECS model is much better for liquid phase densities and isochoric heat capacities. Other derived properties, such as isobaric heat capacity (C_p) and the speed of sound, should also be represented better by the ECS model. Thus, we recommend the ECS model for both pure fluid and mixture computations.

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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 third 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 Boulder, CO.

Figure 1—Calibration data for the liquid densimeter.

Figure 2— Locus of PVT data for HFC-41.

Figure 3—Comparison of calculated bubble point pressures with experimental data for R32/134a: (a) ECS model, (b) CSD equation of state.

Figure 4—Comparison of calculated bubble point pressures with experimental data for R32/125: (a) ECS model, (b) CSD equation of state.

Figure 5—Comparison of calculated isochoric heat capacities with experimental data for R32/134a: (a) ECS model, (b) CSD equation of state.

Figure 6—Comparison of calculated single-phase densities (PVT) with experimental data for R32/134a: (a) ECS model, (b) CSD equation.

Figure 7—Comparison of calculated single-phase densities (PVT) with experimental data for R32/125: (a) ECS model, (b) CSD equation.

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
174.999	15.0243	27.5215

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
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
222.999	6.9410	24.4015
224.000	7.8843	24.3851

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
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
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

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

T	P	ρ
K	MPa	$\text{mol} \cdot \text{dm}^{-3}$
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

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
-56.47	1143.517	51.809

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

T	P	ρ
°F	psia	lb·ft ⁻³
-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
44.33	2733.708	45.360
47.93	2957.494	45.350
51.53	3181.488	45.341

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

T	P	ρ
°F	psia	lb·ft ⁻³
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