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DEVELOPMENT OF MEASUREMENT CAPABILITIES
FOR THE THERMOPHYSICAL PROPERTIES OF ENERGY-RELATED FLUIDS

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DEVELOPMENT OF MEASUREMENT CAPABILITIES
FOR THE THERMOPHYSICAL PROPERTIES OF ENERGY-RELATED FLUIDS

Introduction

This report describes the progress during the fourth year of this five-year project, which began on December 1, 1990. The objectives of the project are to develop state-of-the-art experimental apparatus that can be used to measure the thermophysical properties of a wide range of fluids and fluid mixtures important to the energy, chemical, and energy-related industries and to carry out carefully selected benchmark measurements on key systems. The research is being done by two groups within the Thermophysics Division of the Chemical Science and Technology Laboratory of the National Institute of Standards and Technology (NIST). One group is located in NIST's laboratories in Gaithersburg, Maryland, the other in Boulder, Colorado. The measurement capabilities to be developed include new apparatus for transport properties, thermodynamic properties, phase equilibria properties, and dielectric properties. These new apparatus will extend the existing state of the art for properties measurements and make it possible to study a wide range of complex fluid systems under conditions that have been previously inaccessible. The specific measurement capabilities to be developed are:

1. Thermal Conductivity Apparatus
2. Vibrating Wire Viscometer
3. Dual-Sinker Densimeter
4. High-Temperature Vibrating Tube Densimeter
5. Dynamic Phase Equilibria Apparatus
6. Apparatus for Dilute Solutions
7. Total-Enthalpy Flow Calorimeter
8. Dielectric Constant Apparatus

The research also includes benchmark experimental measurements on pure and mixed alternative refrigerants, on aqueous solutions, and on carefully selected systems consisting of species of diverse size (methane + neopentane) and polarity (methane + ammonia) that are important for the development of predictive models for energy-related fluids.

The following reports summarize the status of each of the individual apparatus development and measurement projects. The projects on the Thermal Conductivity Apparatus, Dual-Sinker Densimeter, High-Temperature Vibrating Tube Densimeter, Apparatus for Dilute Solutions, and Dielectric Constant Apparatus are complete or essentially complete. The projects on the Vibrating Wire Viscometer, Dynamic Phase Equilibria Apparatus, and Total-Enthalpy Flow Calorimeter are progressing well, as are the benchmark measurements.

THERMAL CONDUCTIVITY APPARATUS

Richard A. Perkins

The new tantalum hot-wire cell is complete and can presently be used to measure the thermal conductivity and thermal diffusivity of electrically conducting fluids at temperatures from 220 to 550 K at pressures to 70 MPa. This is currently the only absolute transient hot-wire cell of this type for electrically conducting fluids available in the United States, and it covers a wider temperature range than any tantalum hot-wire cell in the world. The cell is constructed from Hastelloy C-276 for good corrosion resistance in aqueous solutions containing halogen ions. The cell has two tantalum hot wires with 25 μm outside diameters. These wires are anodized to produce a thin (70 nm) film of tantalum pentoxide as an electrical insulation layer. The thickness of the oxide film can be directly controlled by varying the magnitude of the voltage used during the anodization process. Mechanical damage to the film can be easily repaired by anodizing the wire again to the same voltage level when electrical leakage between the wires and the cell wall is detected. The chemical resistance of the oxide film can be increased by application of a polarization voltage between the hot wires and the cell wall. All other wetted materials in the cell are coated with polyimide and teflon for electrical insulation and improved corrosion resistance to 550 K.

Performance of the new tantalum hot-wire cell has been verified with measurements on argon, toluene, and R134a. Performance of both the bare 12.7 μm platinum hot wires and the new coated 25 μm tantalum hot wires has been compared using an IUPAC round-robin sample of R134a. This round-robin test is organized by the IUPAC Subcommittee on Transport Properties and will compare thermal conductivity data obtained by transient hot-wire and light-scattering instruments located in

Canada, the United States, the United Kingdom, Germany, Japan, Portugal, Greece, and Sweden. The initial results of measurements on this IUPAC sample were presented at the 12th Symposium on Thermophysical Properties in June 1994 and have been submitted for publication in the conference proceedings. The results of our initial verification measurements on argon and R134a from 300 to 340 K were reported at the 22nd International Thermal Conductivity Conference in November 1993 and at the 12th DOE Symposium on Energy Engineering Sciences in April 1994. The cell has also been verified with liquid toluene from 300 to 550 K, and these results were presented at the 12th Symposium on Thermophysical Properties in June 1994. The tantalum hot-wire cell is in routine operation and has been used for measurements on both R152a and R143a. It has also been demonstrated that the tantalum hot-wire cell can be operated in an absolute steady-state mode to measure the dilute gas thermal conductivity of argon, R152a, and R143a. The R152a results were reported at the 12th Symposium on Thermophysical Properties in June 1994. The next measurements scheduled for the tantalum hot-wire cell are ammonia, water, and ammonia-water mixtures; ammonia-water mixtures are promising as new working fluids for large-scale power cycles.

A paper entitled, "Measurements of the thermal properties of electrically conducting fluids using coated transient hot wires", was prepared by R.A. Perkins and presented at the 12th Symposium on Energy Engineering Sciences at Argonne, IL, April 27-29, 1994. A copy of that paper is attached as Appendix A of this report.

VIBRATING WIRE VISCOMETER

Richard A. Perkins and Arno Laesecke

The vibrating wire viscometer will be able to measure the viscosity of liquids and gases from 80 to 600 K at pressures to 70 MPa. It will also have the potential for use as a vibrating wire densimeter. Transverse vibrations of the wire are driven by an ac current in the wire in the presence of a permanent magnetic field. The vibrations are monitored using the induced voltage from the wire as it moves in the permanent magnetic field. The frequency of the principal vibration mode is primarily a function of the tension, mechanical properties, and dimensions of the wire. Damping of the wire vibrations is due to the internal mechanical losses and the external viscous drag of any fluid surrounding the

wire. At any given temperature the internal damping can be measured by evacuating the cavity surrounding the wire and characterizing the wire vibration. The wire can be driven in a steady-state mode where the tension of the wire can be determined from the resonant frequency and the viscosity of the fluid can be determined from the bandwidth of the resonance curve. Alternatively, the wire can be driven into transverse vibrations near its resonant frequency, and the transient vibrations can be measured as a function of elapsed time after the drive voltage is turned off. In this case variations in the tension of the wire can be determined from the vibration frequency, and the viscosity can be determined from the logarithmic decrement of the magnitude of the vibrations.

A prototype vibrating wire cell has been constructed and has been used in a number of tests. The prototype cell consists of a single tungsten wire which is 4 cm long. Wires with diameters of 50, 80, and 100 μm have been used in this prototype cell. The prototype cell is tensioned with a single weight so we can explore its use both as a viscometer and as a densimeter. The wire is contained in a coaxial cylindrical cavity with a diameter of 8 mm. The permanent magnetic field is produced by 6 small samarium-cobalt magnets located near the longitudinal center of the wire just outside the coaxial cylindrical cavity. Three 1.3 cm diameter button magnets are located in channels on each side of the wire so that the magnetic field extends over most of the length of the wire. The present cell is designed to operate at frequencies near 1 kHz and has been tested in air and water. Holes are located near the ends of the vibrating wire for measurement of the wire length with a cathetometer. The data acquisition system includes a 80486-based personal computer with a data acquisition card, IEEE-488 interface, synthesized function generator, digital storage scope, digital multimeter, multiplexer, lock-in amplifier, quartz pressure transducer, standard platinum resistance thermometer, and quad output dc power supply to control the cell temperature. The data acquisition card has a 16 bit digital-to-analog converter that can generate the wire excitation current and a multiplexed 16 bit analog-to-digital converter that can measure the induced wire voltage at frequencies up to 100 kHz. The vibrating wire is located in an ac bridge circuit that uses a variable ratio transformer to null the bridge (1 part in 10^6) at a frequency where the wire is not excited. The nulled bridge effectively removes the drive voltage so that the bridge response is due to the induced voltage from the wire moving in the permanent magnetic field.

The final vibrating wire transducer design has been completed, and the transducer is currently being constructed of 316 stainless steel, tungsten, samarium-cobalt, and polyimide. The transducer fits in a 316 stainless-steel pressure vessel with a volume of 0.5 liter. The pressure vessel is rated for pressures to 70 MPa at 425 °C. The transducer is designed to minimize the quantity of sample required for a measurement; the sample volume will be less than 100 cm³. This transducer uses two samarium-cobalt magnets with dimensions of 19 mm x 38 mm x 6 mm which produce a strong magnetic field over the entire length of the wire. The vibrating wire is tungsten with a diameter of 80 μm and is held rigidly using stainless steel collets. The wire is tensioned with a double weight system which compensates for buoyancy forces as the density of the fluid changes surrounding the wire and weights. The central weight is attached to the end of the vibrating wire and is made from tungsten which is quite dense relative to the outer ring-shaped weight which is made from 316 stainless steel. The two weights are designed so that they have the same volume and buoyancy forces acting on them. The two weights are set in opposition using two wires and low-friction jeweled pivot levers located on the base of the magnet assembly. The orientation of the levers and coupling wires between the two weights is offset from the magnetic field by an angle of 90 degrees. This tends to remove degenerate modes of vibration and forces the wire to vibrate in a transverse mode in the direction of the magnetic field. This is crucial since the induced voltage is proportional only to the movement in the plane of the magnetic field. Precession of the wire vibration appears as a low frequency envelope in which the magnitude of the induced voltage fluctuates. At resonance, the amplitude of the induced voltage peaks should be constant, indicating that there is no precession of the wire vibration.

During the next year the vibrating wire transducer and pressure system will be completely tested and located in a cryostat that will allow measurements from 80 to 600 K at pressures to 70 MPa. The design of the cryostat is being finalized. Computer software will be developed to control the transducer temperature and to automate the viscometer measurements as much as possible. The performance of the viscometer will be verified with measurements on nonpolar fluids such as argon gas, liquid toluene, and normal alkanes. The performance will then be tested with polar fluids such as R134a and water. If problems are encountered during measurements of fluids with moderate electrical conductivity, such as R134a and

water, then the tungsten wire will be electrically insulated with an anodic oxide film as we have done with the tantalum hot-wire cell for thermal conductivity measurements. The vibrating wire viscometer will be available for routine measurements during the next year.

DUAL-SINKER DENSIMETER

Mark O. McLinden

This new apparatus covers wide ranges of temperature (80 - 500 K), pressure (up to 35 MPa), and density (50 - 2000 kg/m³) and extends our accuracy for p-V-T measurements by nearly an order of magnitude. A variation on the simple, reliable buoyancy principle is employed: two sinkers of identical mass and surface area, but very different volumes, are weighed while immersed in the fluid of interest. The use of two sinkers leads to a cancelling of effects that would otherwise introduce errors.

The densimeter is essentially complete. The balance, magnetic coupling, sinkers, thermometers, heaters, etc. have been installed in their final positions. Near-ambient measurements of several hydrocarbons have been carried out.

During the current reporting period, most of the effort has gone into developing and debugging control software that allows a high degree of automation. We now have a control program that reads all of the instruments over a computer interface and controls temperatures to the mK level. The program detects when equilibrium is reached (as determined by the average and standard deviations of a specified number of temperature readings), triggers a weighing of the sinkers, records data, and then moves on to the next specified set point. Considerable effort was required in interfacing with the instruments to handle various error conditions that, while occurring only occasionally, would have potentially disastrous consequences if they occurred while the apparatus was operating unattended.

Measurements on a reference fluid such as methane will be carried out to verify the performance of the apparatus. It will then be used for "production" measurements, at state-of-the-art accuracy, on alternative refrigerants, hydrocarbons, and other fluids of energy-related and technical interest.

A paper entitled "Development of a dual-sinker densimeter for high accuracy fluid P-V-T measurements", was prepared by M.O. McLinden and N.V. Frederick and presented at the 11th Symposium on Energy Engineering Sciences at Argonne, IL, May 3-5, 1993. A copy of that paper was included in last year's progress report.

HIGH-TEMPERATURE VIBRATING TUBE DENSIMETER

Ren Fang Chang and Michael R. Moldover

A vibrating-tube densimeter has been developed that operates at temperatures in the range from 300 to 600 K. The heart of the densimeter is a hair pin-shaped tube placed between the poles of a permanent magnet. An alternating electric current flows through the tube and induces an oscillating force on the tube. When the frequency of the current matches one of the natural bending frequencies of the tube, a resonance occurs. The square of the resonance frequency is inversely proportional to the total oscillating mass which includes both the tube's mass and the mass of fluid within it. At each temperature, two measurements are required to calibrate the densimeter -- one to determine the effective spring constant for the bending mode and the other to determine the effective volume within the tube. For calibration, the resonance frequencies are measured with the tube evacuated and with the tube filled with water, a fluid with a well known density.

The densimeter has been tested by measuring the density of toluene in the temperature range 298 K - 578 K and the pressure range 0.1 MPa - 14 MPa. The test measurements were compared with a published correlation [R.D. Goodwin, J. Phys. Chem. Ref. Data 18, 1565 (1989)]. The root-mean-square (rms) deviation of the measured densities from the correlation was 0.45 mg/cm³, which is comparable to the rms deviation of the calibration data from the NBS/NRC Steam Tables; thus, it is essentially the limit of performance of the present instrument.

Despite substantial efforts during the past year to extend the useful operating range of the densimeter to higher temperatures, above 600 K we continue to observe persistent, slow, upward drifts in the resonance frequency in every densimeter we have made, even though they have used very different materials and designs. We have designed, fabricated, and tested no fewer than a dozen prototypes during the past several years. Experts in the Metallurgy Division of

NIST have been unable to explain these observations. In any event, these drifts limit the effective use of the densimeter to temperatures below about 600 K.

One possible strategy to overcoming the obstacle posed by high-temperature drifts in the resonant frequency of the densimeter is to calibrate the densimeter with a fluid of known density each time a sample is measured (under the same conditions of temperature and pressure). This idea has been tested for refrigerants R123 and R141b at room temperature at a pressure of 6 MPa. The results agreed with those in the literature to within 0.2 mg/cm^3 , indicating the viability of this approach.

DYNAMIC PHASE EQUILIBRIA APPARATUS

Cynthia D. Holcomb

The dynamic phase equilibrium apparatus will complement existing low- and high-temperature vapor-liquid apparatus and will incorporate equilibrium and dynamic surface tension measurements. This will be the first apparatus of this type able to measure vapor-liquid equilibria, coexisting densities, equilibrium surface tension, and dynamic surface tension over a wide range of temperatures and pressures. It will extend the temperature and pressure range of our current capabilities by operating in the range from 223 to 423 K at pressures to 40 MPa. The experimental uncertainties of the temperature measurements will be better than 30 mK. The experimental uncertainty of the pressure measurements will be better than 0.05%. The experimental uncertainty of the density measurements should be better than 0.2 kg/m^3 . By having two densimeters, one for liquid and one for vapor, and calibrating each densimeter independently over its operable density, pressure, and temperature ranges, we will reduce the manufacturer's stated experimental uncertainty by a factor of at least two. The experimental uncertainty of the surface tension measurements will be 0.1 mN/m .

Most of the construction for the new apparatus has been completed. The temperature controlled box for the pressure transducers, differential pressure gages, and related valves has been completed. The feed system has been completed. The support structure has been completed and the pumps, densimeters, and cell have been mounted. The heating wires and cooling coils have been installed. The data acquisition computer software is written, but needs

additional testing once the entire apparatus is complete. There are two data acquisition routines. One program monitors the cell temperature, the densimeter temperatures, the pressure, and the densities. The other program uses the information from the first program plus the additional information from the differential pressure gage to determine the surface tension. A temperature controller with battery backup was purchased to allow the system to return to the setpoint after any unexpected power interruptions or fluctuations. The refrigerator will also return to its setpoint after power interruptions or fluctuations. A crane has been obtained for lifting and lowering the apparatus in and out of the dewar.

The remaining construction, which involves piping and crane installation, and calibration and performance testing of the complete apparatus will be completed in the near future. Measurements will be carried out subsequently on refrigerant mixtures proposed as alternatives for R22.

APPARATUS FOR DILUTE SOLUTIONS

Lloyd A. Weber

The objectives of this task were to develop apparatus for making accurate vapor pressure measurements of pure fluids and for measuring infinite dilution activity coefficients of binary mixtures. Such data are extremely useful for calculating the vapor-liquid equilibrium behavior of solutions.

In this and previous reporting periods, we have developed and evaluated a new comparative glass ebulliometer for both pure fluids and mixtures and a new, semi-automated all-metal system for measurements on refrigerant mixtures over a wide range of temperatures at elevated pressures (see below). To our knowledge, this metal ebulliometer is the first instrument of its kind to cover such a range of conditions. We have also completed and tested a new all-stainless-steel ebulliometer for measuring vapor pressures of pure fluids directly at elevated pressures. This ebulliometer is of the same general size and design as a sapphire device that it replaces.

The final construction and evaluation of the all-metal comparative ebulliometer apparatus were completed during the current reporting period. With regard to the

construction, a loading system for injecting small measured doses of gaseous solutes at elevated pressures and ambient temperature was built and tested on two binary refrigerant systems of interest (see Benchmark Measurements). This adaptation is unique in the design of ebulliometers, which are normally used only with liquid samples.

The important condensed vapor holdup correction was determined from measurements on the system R123 (solvent) + R124 (solute) at 292 K. We found that during operation 1.8 cm³ (of a 50 cm³ liquid sample) of condensed vapor is present on the walls of the boiler at all times. This quantity is important for adjusting the composition of the liquid in the boiler.

The apparatus has been used thus far for measurements in the range 240 - 333 K at pressures between 70 and 1786 kPa. However, it should be capable of operation at temperatures down to 230 K and as high as 400 K; work at pressures as high as 3000 kPa should also be possible.

Besides phase equilibrium studies on binary mixtures, the all-metal comparative apparatus is also useful for making vapor pressure measurements on pure fluids. In addition to the pure fluid vapor pressure measurements and the contamination effect studies noted in the last report, we have made more vapor pressure measurements on pure fluids, notably R143a for the air conditioning and refrigeration industry, and R236ea, R245ca, R236fa, and R245fa (all partially fluorinated propanes) for the Environmental Protection Agency and the U.S. Navy.

A paper entitled, "Ebulliometers for measuring the properties of fluids and fluid mixtures", was prepared by L.A. Weber and presented at the 12th Symposium on Energy Engineering Sciences at Argonne, IL, April 27-29, 1994. A copy of that paper is attached as Appendix B of this report.

THERMOELECTRIC TOTAL-ENTHALPY FLOW CALORIMETER

Joseph W. Magee

The constant-pressure flow calorimeter will operate between 200 and 700 K at pressures to 20 MPa. It will be well-suited for measurements of total enthalpy of fluids of interest to the energy industry, including reactive, corrosive and

thermally-labile substances. It will produce benchmark-quality data with uncertainties of approximately $\pm 0.2\%$ at temperatures to 500 K. The system will use a thermoelectric cooling element to remove energy from the calorimeter at a precisely controlled rate. Energy will be supplied to the calorimeter either by an electrical heater or by the sample fluid flowing through the apparatus. The enthalpy of the fluid will be measured by observing changes in the power delivered by the electrical heater required to maintain the calorimeter at constant temperature.

The overall design was finalized during the first year, and, in the second year, manufacturers of the key elements of this design were selected and instruments were purchased. During the third year, construction began on the components of the calorimeter. The construction of the apparatus has been divided into four sections: pre-heater, connecting tube, calorimeter, and pressure control. During the fourth or current year, the pre-heater, connecting tube, and calorimeter sections of the apparatus are being constructed. The pre-heater section consists of a solid aluminum cylinder with parallel spiral grooves machined on the surface for the flow tubing and coolant tubing. It is surrounded by a tight-fitting clamshell that supports five high-power heaters. This section is capable of heating or cooling a sample to an outlet temperature between 200 and 700 K, as verified by a standard platinum resistance thermometer. For the calorimeter section, an aluminum disk sandwich was machined with a planar spiral groove for the flow tubing. The calorimeter section is an evacuated aluminum vessel which holds this metallic sandwich and adds (or removes) energy to (or from) the flowing sample to bring the final temperature to 298.15 K. This section is placed in a large aluminum block which is regulated at constant temperature. The metallic elements of the connecting tube section have been machined and are being assembled. This assembly consists of the flow tubing which connects the pre-heater and calorimeter sections and the surrounding layers of thermal shielding which employ fine-wire thermocouples and two independent heaters.

During the coming year, the remaining components of the apparatus will be assembled and then the entire apparatus will be tested. The flow control system will be assembled consisting of an automated high-pressure syringe pump, an oscillating quartz crystal pressure transducer, and a back-pressure regulator

that is capable of maintaining the back pressure in the flow system to approximately ± 2 kPa. For the calorimeter section, the matching heater and thermoelectric cooling device will be attached to the lower surface of the metallic disk sandwich. Then, fine thermocouples will be attached to measure the temperature profile on this assembly. Miniature thermistors will be fed by metal-sheathed coaxial cable into the flow tubing to measure the fluid temperature in both the inlet and outlet streams. Leak-free seals will be developed which permit the coaxial cable to move inside the pressurized flow system. Computer programs in the C language are being developed to control all aspects of this flow calorimeter to achieve a high level of automation. After the assembly is complete, enthalpy measurements on steam will be carried out to performance test the apparatus.

DIELECTRIC CONSTANT APPARATUS

Anthony R.H. Goodwin, and M.R. Moldover

The objective of the project was to extend the range of conditions under which accurate dielectric constant measurements can be made. During previous reporting periods, we developed and evaluated parallel-plate and concentric cylinder capacitors as well as a reentrant radio-frequency (rf) cavity that can operate as a resonator near 375 MHz to measure changes in the dielectric constant of fluids within it. A paper entitled "Dielectric studies of fluids with reentrant resonators", was prepared by A.R.H. Goodwin and M.R. Moldover and presented at the 11th Symposium on Energy Engineering Sciences at Argonne, IL, May 3-5, 1993. A copy of that paper was included in last year's progress report.

BENCHMARK MEASUREMENTS

We have used the metal comparative ebulliometer described above to perform thermodynamic studies of two binary refrigerant systems. The first system, R22 + R143a at 275 K, was used to test the apparatus since Morrison and McLinden had predicted that it would have nearly ideal behavior (in the sense of Raoult's law). We found that the activity coefficients for both components varied between 0.984 and unity (unity signifying ideal behavior), thus verifying the prediction. In addition, we found very small values of the excess Gibbs free energy, less than 10 J/mol. To our knowledge, our results constitute the only published data

in the literature on this system (which is marketed under a trade name by Atochem).

Following the work on R22 + R143a, we conducted an extensive study of the system R32 + R134a at 260, 280, and 300 K. Measurements of $(dT/dx_1)_p^\circ$ and $(dT/dx_2)_p^\circ$ -- the slopes of each end of the bubble curve at infinite dilution -- led to the determination of the activity coefficients at infinite dilution, γ_1° and γ_2° . We then used Wilson's model, a widely-used model for the excess Gibbs free energy (G^E), to derive activity coefficients and values of G^E at all concentrations, and also to derive phase diagrams in the form of P-x-y plots. Our measurements over a range of temperatures allowed us to calculate the excess enthalpy and entropy of mixing, H^E and S^E , respectively, from the temperature variation of G^E , and from these quantities all of the equilibrium thermodynamic properties of the two-phase system are calculable. We are not aware of any other results for this system at temperatures as low as 260 K. This work made extensive use of the results of some of our Benchmark Measurements from last year - the gas-phase virial coefficients of this binary mixture.

BRIEF WORK STATEMENT FOR THE PERIOD
DECEMBER 1, 1994 - NOVEMBER 30, 1995

Complete the development and evaluation of the vibrating wire viscometer, the dynamic phase equilibria apparatus, and the total-enthalpy flow calorimeter. Continue to perform benchmark measurements on CFC and HCFC alternatives, including mixtures. Perform benchmark measurements on aqueous systems and on systems consisting of species of diverse size (methane + neopentane) and polarity (methane + ammonia).

Budget removed

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PUBLICATIONS RELATED TO DE-A105-88ER13823

FOR THE APPROXIMATE PERIOD DECEMBER 1, 1990 - JULY 31, 1994

The following publications describe applications of the apparatus developed under this contract as well as the development of the apparatus themselves. Asterisks indicate publications added since the last report.

- * Assael, M.J., Nagasaka, Y., Nieto de Castro, C.A., Perkins, R.A., Stom, K., Vogel, E., and Wakeham, W.A., Round-Robin on the Transport Properties of R134a, Proceedings of the Twelfth Symposium on Thermophysical Properties, June 19-24, 1994, Boulder, Colorado, Int. J. Thermophysics (submitted).
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- * Boyes, S.J. and Weber, L.A., Vapor-Pressures and Gas-Phase (P, ρ , T) Data for Pentafluoroethane (R125), J. Chem. Thermodynamics (in press).
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- Defibaugh, D.R., Morrison, G., and Weber, L.A., Thermodynamic Properties of Difluoromethane (R32), J. Chem. & Eng. 39, 333 (1994).
- * Defibaugh, D.R. and Morrison, G., Compressed Liquid Densities, Saturated Liquid Densities and Vapor Pressures of 1,1-Difluoroethane, J. Chem. & Eng. Data (submitted).

- * Defibaugh, D.R. and Silva, A.M., Compressed Liquid Densities, Saturated Liquid Densities and Vapor Pressures of 1,1,1,2,3,3-Hexafluoropropane, Proceedings of the Twelfth Symposium on Thermophysical Properties, June 19-24, Boulder, Colorado, Int. J. Thermophysics (submitted).
- Diller, D.E., Aragon, A.S., and Laesecke, A., Measurements of the Viscosities of Saturated and Compressed Liquid Chlorodifluoromethane (R22), Int. J. Refrig. 16 (1993).
- Diller, D.E., Torsional Crystal Viscometer, IUPAC Volume on Transport Properties (1991).
- Diller, D.E., Aragon, A.S., and Laesecke, A., Measurements of the Viscosities of Compressed Liquid Air at Temperatures between 70 and 130 K, Cryogenics 31, 1070 (1991).
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