

THERMAL CONDUCTIVITY OF R134a*

A. Laesecke^a, R.A. Perkins^a, and C.A. Nieto de Castro^b

^a*Thermophysics Division 838.02, National Institute of Standards and Technology, Boulder, Colorado 80303 (U.S.A.)*

^b*Departamento de Quimica, Faculdade de Ciencias, Universidade de Lisboa, 1700 Lisboa (Portugal)*

Key words: liquid; R134a; supercritical fluid; 1,1,1,2-tetrafluoroethane; thermal conductivity; transient hot wire instrument; vapor

ABSTRACT

Thermal conductivity measurements are reported for the alternative refrigerant 1,1,1,2-tetrafluoroethane (R134a). These measurements were made over the temperature range from 200 to 390 K at pressures to 70 MPa. Data are reported for the liquid, vapor, and supercritical fluid phases. A significant critical enhancement is observed for R134a. A thermal conductivity surface, which fits our data to $\pm 3.8\%$ at 95% confidence, is provided for R134a. Correlations are also provided for the saturated vapor and saturated liquid thermal conductivity of R134a. Comparisons are made with other available thermal conductivity data for the dilute gas, saturated vapor, and saturated liquid.

INTRODUCTION

The emission of chlorofluorocarbons, such as dichlorodifluoromethane (R12), has been identified as the main cause for stratospheric ozone depletion (Prather and Watson, 1990). The leading replacement fluid for R12 is R134a, which has zero ozone depletion potential (Fisher et al., 1990a). In addition, the global warming potential of R134a is much lower than R12 (Fisher et al., 1990b). Feasibility studies are now being conducted to assess the performance of refrigeration systems which use R134a as a working fluid. Petersson and Thorsell (1990) state that there is "a substantial amount of data" on the thermodynamic and chemical properties of R134a

*Contribution of the National Institute of Standards and Technology, not subject to U.S. copyright.

exist. A closer inspection reveals, however, that most of these data are preliminary and cover a limited range of temperature and pressure. This contribution presents accurate thermal conductivity data and correlations for R134a at temperatures from 200 K to 390 K with pressures up to 70 MPa. This pressure range exceeds considerably the region in which heat pumps and refrigeration cycles operate. Nevertheless, such wide-range measurements are necessary for a full understanding of the thermal conductivity of R134a.

EXPERIMENTAL

The thermal conductivity measurements were made with two transient hot-wire instruments at the National Institute of Standards and Technology (NIST). Detailed description of these instruments and their operation has been provided previously (Roder, 1981; Perkins et al., 1991). These instruments use 12.7 μm diameter platinum wires, which are immersed in the fluid of interest and serve simultaneously as transient electrical heat sources and as resistance thermometers. A typical experiment is 1 s in duration with a final temperature rise of 1 to 4 K. During a 1 s experiment, the temperature rise is recorded every 4 ms for a total of 250 data points. The instruments are designed to approximate the transient line source model as closely as possible. Deviations from this model are handled as corrections. Ideally the wire temperature rise ΔT is given as a function of elapsed time t by

$$\Delta T = \frac{q}{4\pi\lambda} \ln \left(\frac{4at}{r_o^2 C} \right) = \frac{q}{4\pi\lambda} \ln \left(\frac{4a}{r_o^2 C} \right) + \frac{q}{4\pi\lambda} \ln(t), \quad (1)$$

where q is the power input per unit length of wire, r_o is the radius of the wire, λ is the thermal conductivity, $a = \lambda / \rho C_p$ is the thermal diffusivity, ρ is the density, C_p is the isobaric heat capacity, and $C = 1.781\ldots$ is the exponential of Euler's constant. The fluid thermal conductivity can be found from eqn. (1) as the slope of the line through a plot of the temperature rise versus the logarithm of elapsed time. In the present study, the low temperature instrument (Roder, 1981) is used for temperatures from 200 to 300 K at pressures to 70 MPa. The high temperature instrument (Perkins et al., 1991) is used for temperatures from 300 to 390 K at pressures to 70 MPa. The sample of R134a used in this study was analyzed before use and found to contain less than 5 ppm of organic impurities, 85 ppm of air, and 126 ppm of water. The sample was further dried over 4AXH7 molecular sieve.

R134a is a polar fluid with very good solvent properties. As a result, the liquid-phase thermal conductivity measurements required special procedures. When liquid R134a was present in the thermal conductivity cell, the electrical isolation between the bare platinum hot wires and the cell wall degraded to about 5 M Ω . In normal operation with a nonpolar fluid, this isolation is greater than 40 M Ω . In addition, an electrochemical potential was observed between the hot wires and the cell wall. This phenomenon has been reported previously for liquid chlorobenzene (Nieto

de Castro et al., 1989) and liquid R134a (Ross et al., 1990). These liquid-phase electrical properties are thought to be due to the solubility of very dilute quantities of ionic impurities. These impurities are present in such dilute concentrations that their presence does not alter significantly the thermodynamic and transport properties of the fluid. The liquid phase electrical conduction between the hot wires and the cell wall does, however, introduce an error in the transient hot-wire thermal conductivity measurement. This error can be eliminated by application of a fixed dc polarization voltage between the cell wall and the hot wires (Nieto de Castro et al., 1989; Ross et al., 1990). This polarization voltage establishes a compact double layer in the resulting electric field around the hot wires. Once the compact double layer is established, the presence of the ions does not alter the transient hot-wire thermal conductivity measurement. We have found that the scatter in the measured thermal conductivity, with varying applied powers, is $\pm 0.3\%$ when a polarization voltage of greater than 6 V is used for liquid R134a. This uncertainty is for a 95% confidence interval with temperature rises from 1.75 to 3.75 K. All liquid phase and supercritical fluid measurements were made in the presence of a 6 V polarization voltage. The vapor-phase thermal conductivity measurements do not require any polarization voltage.

The full set of thermal conductivity measurements is shown in Fig. 1. These thermal conductivity values are tabulated in Table 1 as a function of temperature (ITS-68), pressure, and density. The reported density was obtained from the equation of state of Huber and Ely (1991a). Each thermal conductivity data point in Table 1 is the average of at least 4 different temperature rises, or applied powers, which have been adjusted to the nominal isotherm temperature using the correlation developed in this work.

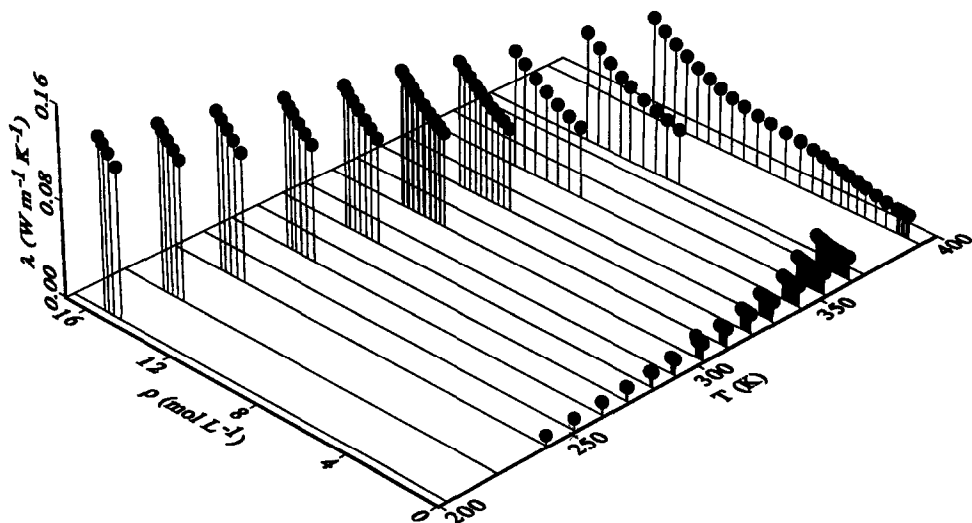


Fig. 1. Thermal conductivity surface for R134a.

TABLE 1

Thermal conductivity data for the alternative refrigerant R134a. Temperature is defined according to IPTS-68.

| P (MPa) | ρ (mol L ⁻¹) | λ (W m ⁻¹ K ⁻¹) | P (MPa) | ρ (mol L ⁻¹) | λ (W m ⁻¹ K ⁻¹) |
|----------------------------------|-------------------------------|--|---------|-------------------------------|--|
| Isotherm Temperature = 203.000 K | | | | | |
| 66.395 | 15.527 | 0.14495 | 27.502 | 15.086 | 0.13473 |
| 47.954 | 15.331 | 0.14043 | 2.342 | 14.727 | 0.12659 |
| Isotherm Temperature = 222.000 K | | | | | |
| 66.705 | 15.140 | 0.13954 | 15.940 | 14.460 | 0.12400 |
| 49.779 | 14.941 | 0.13519 | 1.301 | 14.198 | 0.11790 |
| 32.629 | 14.714 | 0.12976 | | | |
| Isotherm Temperature = 241.000 K | | | | | |
| 67.850 | 14.776 | 0.13358 | 17.126 | 14.011 | 0.11603 |
| 50.938 | 14.556 | 0.12850 | 1.340 | 13.673 | 0.10885 |
| 34.004 | 14.305 | 0.12258 | 0.047 | 0.024 | 0.00896 |
| Isotherm Temperature = 252.000 K | | | | | |
| 0.084 | 0.042 | 0.00993 | | | |
| Isotherm Temperature = 263.000 K | | | | | |
| 65.426 | 14.317 | 0.12565 | 13.594 | 13.374 | 0.10508 |
| 50.639 | 14.097 | 0.12058 | 2.108 | 13.055 | 0.09889 |
| 39.758 | 13.916 | 0.11661 | 0.142 | 0.068 | 0.01087 |
| 25.990 | 13.654 | 0.11071 | 0.068 | 0.032 | 0.01079 |
| Isotherm Temperature = 273.000 K | | | | | |
| 0.247 | 0.118 | 0.01170 | 0.090 | 0.041 | 0.01173 |
| 0.166 | 0.077 | 0.01169 | | | |
| Isotherm Temperature = 283.000 K | | | | | |
| 66.314 | 13.950 | 0.11978 | 1.705 | 12.411 | 0.08952 |
| 54.805 | 13.762 | 0.11570 | 0.357 | 0.168 | 0.01264 |
| 41.713 | 13.522 | 0.11055 | 0.285 | 0.131 | 0.01262 |
| 30.050 | 13.274 | 0.10552 | 0.221 | 0.100 | 0.01254 |
| 18.619 | 12.985 | 0.09982 | 0.133 | 0.059 | 0.01250 |
| 10.095 | 12.726 | 0.09486 | | | |
| Isotherm Temperature = 292.000 K | | | | | |
| 0.498 | 0.233 | 0.01341 | 0.296 | 0.131 | 0.01328 |
| 0.391 | 0.177 | 0.01336 | 0.147 | 0.063 | 0.01326 |
| Isotherm Temperature = 303.000 K | | | | | |
| 65.817 | 13.567 | 0.11413 | 52.789 | 13.327 | 0.10915 |

TABLE 1 (continued)

| P (MPa) | ρ (mol L ⁻¹) | λ (W m ⁻¹ K ⁻¹) | P (MPa) | ρ (mol L ⁻¹) | λ (W m ⁻¹ K ⁻¹) |
|----------------------------------|-------------------------------|--|---------|-------------------------------|--|
| 41.687 | 13.092 | 0.10437 | 4.387 | 11.857 | 0.08400 |
| 31.981 | 12.856 | 0.10026 | 0.609 | 0.277 | 0.01433 |
| 21.682 | 12.559 | 0.09485 | 0.362 | 0.155 | 0.01415 |
| 14.107 | 12.295 | 0.09056 | 0.252 | 0.105 | 0.01404 |
| 8.488 | 12.060 | 0.08707 | 0.122 | 0.050 | 0.01409 |
| Isotherm Temperature = 313.000 K | | | | | |
| 0.809 | 0.368 | 0.01555 | 0.466 | 0.195 | 0.01535 |
| 0.731 | 0.326 | 0.01545 | 0.308 | 0.125 | 0.01516 |
| 0.657 | 0.287 | 0.01532 | 0.201 | 0.080 | 0.01519 |
| 0.582 | 0.250 | 0.01523 | | | |
| Isotherm Temperature = 323.000 K | | | | | |
| 67.429 | 13.227 | 0.10623 | 1.124 | 0.523 | 0.01659 |
| 56.139 | 13.001 | 0.10198 | 1.067 | 0.488 | 0.01647 |
| 45.326 | 12.753 | 0.09730 | 0.986 | 0.442 | 0.01632 |
| 35.256 | 12.484 | 0.09290 | 0.899 | 0.395 | 0.01623 |
| 27.547 | 12.243 | 0.08893 | 0.784 | 0.335 | 0.01599 |
| 20.361 | 11.978 | 0.08484 | 0.702 | 0.295 | 0.01600 |
| 14.051 | 11.696 | 0.08074 | 0.603 | 0.249 | 0.01588 |
| 9.021 | 11.420 | 0.07720 | 0.484 | 0.195 | 0.01575 |
| 5.412 | 11.176 | 0.07437 | 0.367 | 0.145 | 0.01574 |
| 1.828 | 10.866 | 0.07087 | 0.257 | 0.100 | 0.01573 |
| Isotherm Temperature = 332.000 K | | | | | |
| 1.438 | 0.683 | 0.01786 | 0.832 | 0.344 | 0.01668 |
| 1.367 | 0.637 | 0.01761 | 0.742 | 0.302 | 0.01662 |
| 1.282 | 0.585 | 0.01731 | 0.637 | 0.254 | 0.01655 |
| 1.210 | 0.542 | 0.01710 | 0.499 | 0.194 | 0.01651 |
| 1.105 | 0.483 | 0.01700 | 0.388 | 0.149 | 0.01667 |
| 1.042 | 0.449 | 0.01691 | 0.264 | 0.099 | 0.01670 |
| 0.947 | 0.400 | 0.01682 | | | |
| Isotherm Temperature = 343.000 K | | | | | |
| 68.201 | 12.880 | 0.09851 | 1.431 | 0.628 | 0.01806 |
| 49.354 | 12.441 | 0.09115 | 1.349 | 0.582 | 0.01770 |
| 32.628 | 11.930 | 0.08312 | 1.252 | 0.530 | 0.01749 |
| 20.411 | 11.415 | 0.07625 | 1.172 | 0.488 | 0.01742 |
| 11.784 | 10.894 | 0.07023 | 1.061 | 0.434 | 0.01742 |
| 6.032 | 10.370 | 0.06503 | 0.948 | 0.380 | 0.01730 |
| 2.397 | 9.831 | 0.06075 | 0.827 | 0.325 | 0.01720 |
| 1.779 | 0.850 | 0.01901 | 0.753 | 0.292 | 0.01744 |
| 1.728 | 0.815 | 0.01874 | 0.635 | 0.242 | 0.01743 |
| 1.658 | 0.767 | 0.01868 | 0.533 | 0.200 | 0.01742 |
| 1.586 | 0.721 | 0.01839 | 0.395 | 0.146 | 0.01735 |
| 1.518 | 0.680 | 0.01818 | | | |

TABLE 1 (continued)

| P (MPa) | ρ (mol L ⁻¹) | λ (W m ⁻¹ K ⁻¹) | P (MPa) | ρ (mol L ⁻¹) | λ (W m ⁻¹ K ⁻¹) |
|----------------------------------|-------------------------------|--|---------|-------------------------------|--|
| Isotherm Temperature = 353.000 K | | | | | |
| 2.398 | 1.255 | 0.02083 | 1.504 | 0.630 | 0.01792 |
| 2.365 | 1.222 | 0.02065 | 1.413 | 0.582 | 0.01778 |
| 2.325 | 1.186 | 0.02048 | 1.337 | 0.544 | 0.01774 |
| 2.274 | 1.141 | 0.02016 | 1.226 | 0.490 | 0.01766 |
| 2.223 | 1.098 | 0.01986 | 1.197 | 0.476 | 0.01754 |
| 2.163 | 1.051 | 0.01969 | 1.125 | 0.443 | 0.01755 |
| 2.107 | 1.007 | 0.01948 | 1.007 | 0.389 | 0.01742 |
| 2.041 | 0.959 | 0.01918 | 0.903 | 0.344 | 0.01745 |
| 1.977 | 0.915 | 0.01903 | 0.785 | 0.294 | 0.01738 |
| 1.914 | 0.872 | 0.01882 | 0.685 | 0.253 | 0.01740 |
| 1.823 | 0.814 | 0.01860 | 0.543 | 0.197 | 0.01744 |
| 1.763 | 0.777 | 0.01837 | 0.422 | 0.151 | 0.01756 |
| 1.687 | 0.732 | 0.01827 | 0.273 | 0.096 | 0.01772 |
| 1.610 | 0.688 | 0.01806 | | | |
| Isotherm Temperature = 364.000 K | | | | | |
| 2.898 | 1.558 | 0.02413 | 2.033 | 0.877 | 0.01967 |
| 2.867 | 1.524 | 0.02388 | 1.945 | 0.825 | 0.01957 |
| 2.831 | 1.486 | 0.02347 | 1.852 | 0.773 | 0.01931 |
| 2.796 | 1.450 | 0.02314 | 1.778 | 0.733 | 0.01919 |
| 2.745 | 1.402 | 0.02279 | 1.692 | 0.688 | 0.01907 |
| 2.703 | 1.362 | 0.02250 | 1.601 | 0.641 | 0.01933 |
| 2.645 | 1.311 | 0.02231 | 1.493 | 0.588 | 0.01924 |
| 2.600 | 1.273 | 0.02188 | 1.373 | 0.532 | 0.01907 |
| 2.549 | 1.231 | 0.02156 | 1.270 | 0.485 | 0.01883 |
| 2.491 | 1.185 | 0.02133 | 1.181 | 0.445 | 0.01878 |
| 2.435 | 1.143 | 0.02103 | 1.083 | 0.403 | 0.01853 |
| 2.385 | 1.107 | 0.02090 | 0.954 | 0.350 | 0.01852 |
| 2.309 | 1.053 | 0.02059 | 0.823 | 0.297 | 0.01847 |
| 2.255 | 1.017 | 0.02048 | 0.697 | 0.248 | 0.01839 |
| 2.166 | 0.958 | 0.02002 | 0.569 | 0.199 | 0.01878 |
| 2.107 | 0.922 | 0.01994 | 0.422 | 0.146 | 0.01863 |
| Isotherm Temperature = 369.000 K | | | | | |
| 67.800 | 12.406 | 0.09231 | 17.196 | 10.400 | 0.06374 |
| 67.886 | 12.408 | 0.09215 | 11.051 | 9.789 | 0.05815 |
| 47.969 | 11.867 | 0.08378 | 7.486 | 9.221 | 0.05392 |
| 33.979 | 11.356 | 0.07545 | 5.571 | 8.721 | 0.05106 |
| 23.597 | 10.838 | 0.06826 | 4.339 | 8.152 | 0.04777 |
| Isotherm Temperature = 393.000 K | | | | | |
| 65.708 | 11.926 | 0.08567 | 15.665 | 9.373 | 0.05581 |
| 49.783 | 11.436 | 0.07836 | 12.203 | 8.856 | 0.05170 |
| 37.264 | 10.932 | 0.07171 | 9.770 | 8.316 | 0.04849 |
| 27.810 | 10.422 | 0.06603 | 8.157 | 7.761 | 0.04606 |
| 20.720 | 9.899 | 0.06025 | 7.085 | 7.158 | 0.04387 |

TABLE 1 (continued)

| P (MPa) | ρ (mol L ⁻¹) | λ (W m ⁻¹ K ⁻¹) | P (MPa) | ρ (mol L ⁻¹) | λ (W m ⁻¹ K ⁻¹) |
|---------|-------------------------------|--|---------|-------------------------------|--|
| 6.471 | 6.581 | 0.04278 | 4.404 | 2.377 | 0.02570 |
| 6.031 | 5.896 | 0.04133 | 3.954 | 1.920 | 0.02359 |
| 5.756 | 5.252 | 0.04049 | 3.360 | 1.464 | 0.02186 |
| 5.755 | 5.250 | 0.03957 | 2.541 | 0.987 | 0.02051 |
| 5.556 | 4.687 | 0.03794 | 2.342 | 0.888 | 0.02042 |
| 5.404 | 4.250 | 0.03582 | 2.108 | 0.778 | 0.02021 |
| 5.255 | 3.850 | 0.03356 | 1.907 | 0.689 | 0.02000 |
| 5.076 | 3.433 | 0.03128 | 1.666 | 0.588 | 0.01987 |
| 4.913 | 3.114 | 0.02946 | 1.419 | 0.488 | 0.01975 |
| 4.676 | 2.730 | 0.02745 | | | |

ANALYSIS

The results presented in Table 1 represent a significant addition to the thermal conductivity data that are available for R134a. Analysis of the present data is based on temperatures defined according to IPTS-68 for consistency with the other available data sets. The thermal conductivity is divided into three terms according to

$$\lambda = \lambda_0(T) + \lambda_{\text{ex}}(\rho) + \lambda_{\text{cr}}(T, \rho), \quad (2)$$

where λ_0 is the dilute gas thermal conductivity, λ_{ex} is the excess thermal conductivity, and λ_{cr} is the thermal conductivity critical enhancement.

Thermal conductivity of the dilute gas

The thermal conductivity of the dilute gas is obtained by a linear extrapolation of the low-density data along each isotherm. The dilute gas thermal conductivity for R134a is given by

$$\lambda_0 = -2.4177 \times 10^{-2} + 1.7664 \times 10^{-4} T - 1.6469 \times 10^{-7} T^2, \quad (3)$$

where λ_0 is in W m⁻¹ K⁻¹ and T is in K. Deviations between the available dilute gas thermal conductivity data and eqn. (3) are shown in Figure 2. There is good agreement between our dilute gas thermal conductivity extrapolations and the data of Ruvinski et al. (1990). The data of Shankland (1990) are higher by up to 7%.

Excess thermal conductivity

The excess thermal conductivity and the critical enhancement are obtained by a global fit of the data after the dilute gas term has been subtracted. The excess thermal conductivity is given by

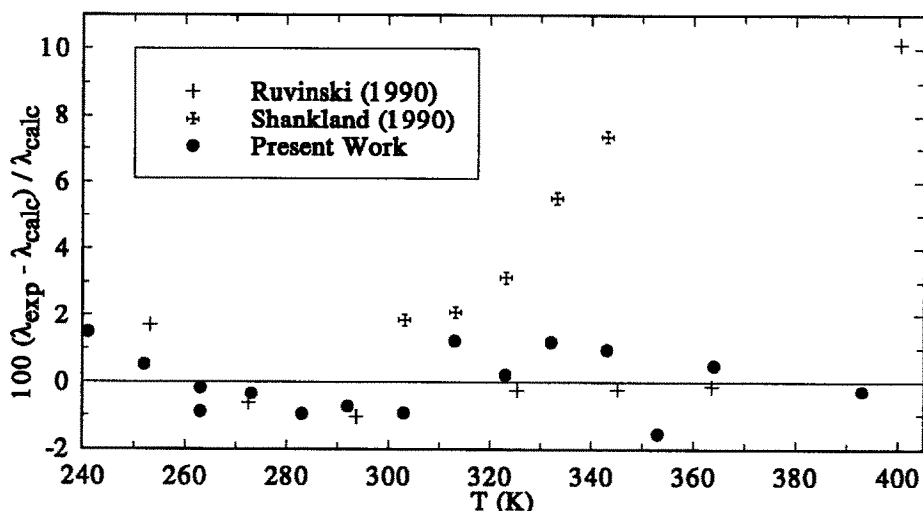


Fig. 2. Deviations between the experimental data and eqn. (3) for the dilute gas thermal conductivity of R134a.

$$\lambda_{\text{ex}} = 9.7756 \times 10^{-5} \rho + 1.5938 \times 10^{-4} \rho^2 + 2.2174 \times 10^{-5} \rho^3 + 3.4660 \times 10^{-7} \rho^4, \quad (4)$$

where λ_{ex} is in $\text{W m}^{-1} \text{K}^{-1}$ and ρ is in mol L^{-1} . The excess thermal conductivity is shown in Figure 3 along with the curve of eqn. (4).

Thermal conductivity critical enhancement

Olchowy and Sengers (1988) have developed a solution to the mode-coupling equations which describe the thermal conductivity critical enhancement. Based on this solution, the thermal conductivity critical enhancement is described by

$$\lambda_{\text{cr}} = \frac{R_c k_B T \rho C_p}{6\pi\eta\xi} (\Omega - \Omega_0), \quad (5)$$

where R_c is a universal critical amplitude, k_B is the Boltzmann constant, η is the shear viscosity, ξ is the correlation length, and Ω and Ω_0 are complicated functions of T and ρ (Olchowy and Sengers, 1988). The correlation length in eqn. (5) is given by

$$\xi = \xi_0 \left[\frac{P_c \rho}{\Gamma \rho_c^2} \right]^{\nu\gamma} \left[\left. \frac{\partial \rho(\rho, T)}{\partial P} \right|_T - \left(\frac{T_r}{T} \right) \left. \frac{\partial \rho(\rho, T_r)}{\partial P} \right|_T \right]^{\nu\gamma}. \quad (6)$$

In eqn. (6) $\nu=0.63$ and $\gamma=1.2415$ are universal scaling exponents, while $\Gamma=0.0498$ and

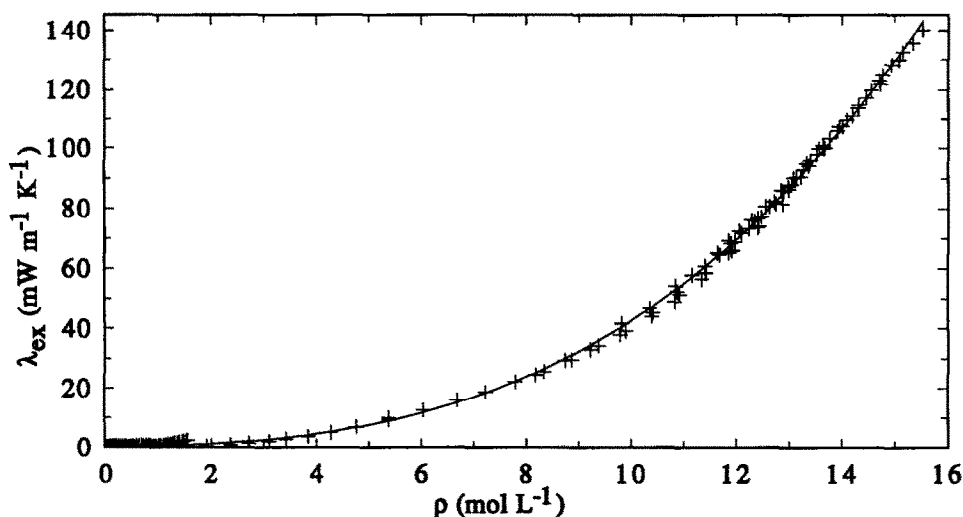


Fig. 3. Excess thermal conductivity for R134a. The solid curve is given by eqn. (4).

$\xi_0 = 0.2019$ nm are fluid specific amplitudes (Tang et al., 1991).

The theory of Olchowy and Sengers (1988) requires fluid compressibility and heat capacities both near the critical point and at reduced temperatures of 2.5 times the critical temperature. The equation of state which we have used for R134a (Huber and Ely, 1991a) should provide reasonable estimates for these properties in the extended critical region. For consistency with the equation of state we have selected the critical temperature ($T_c = 374.255$ K), critical pressure ($P_c = 4.0603$ MPa), and critical density ($\rho_c = 5.017$ mol L⁻¹) of Huber and Ely (1991a). The theory also requires estimates for the background shear viscosity which is obtained from the corresponding states theory of Huber and Ely (1991b).

The reduced temperature T_r , where the critical enhancement vanishes, is defined to be 2.5 times the critical temperature. For R134a the optimum value for the wave-number cutoff is found to be $q_D^{-1} = 0.312$ nm. The thermal conductivity surface given by eqns. (2-6) represents our R134a data to within $\pm 3.8\%$ at 95% confidence. The largest deviations are near the critical point for the 364 K, 369 K, and 390 K isotherms. These deviations should be reduced through application of a crossover equation of state in this region (Tang et al., 1991).

Saturated vapor thermal conductivity

The saturated-vapor thermal conductivity is obtained by adjusting the vapor data closest to saturation, using the correlation of eqns. (2-6), to the saturation boundary as determined by Huber and Ely (1991). These adjusted thermal conductivities are then fit to a simple polynomial in temperature given by

$$\lambda_{sv} = -9.7578 \times 10^{-2} + 1.0504 \times 10^{-3} T - 3.6079 \times 10^{-6} T^2 + 4.4965 \times 10^{-9} T^3, \quad (7)$$

where the saturated vapor thermal conductivity λ_{sv} is in $\text{W m}^{-1} \text{K}^{-1}$, and T is in K. Deviations between the available saturated vapor thermal conductivity data and this correlation are shown in Figure 4. Our data are in very good agreement with the data of Ross et al. (1990) and Ruvinski et al. (1990) from 240 to 350 K. The data of Gross et al. (1990) are systematically higher than our data by about 3%. Above 350 K all the available data is higher than this correlation. This polynomial correlation is not able to accommodate the divergence in the thermal conductivity near the critical temperature. The correlation of eqns. (2-6) fits the data much better in this region.

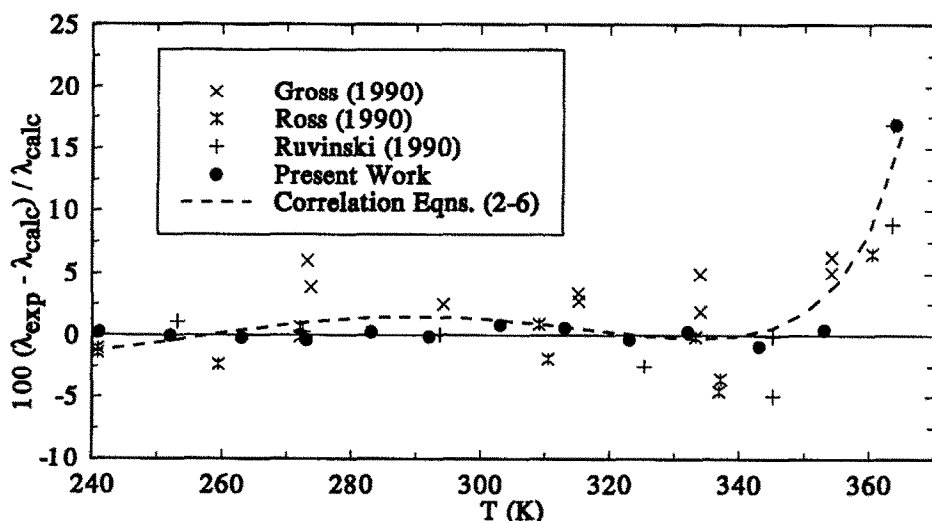


Fig. 4. Deviations between the experimental data and eqn. (7) for the saturated vapor thermal conductivity of R134a.

Saturated liquid thermal conductivity

The saturated liquid thermal conductivity is obtained by adjusting the liquid data which are closest to saturation, with the correlation of eqns. (2,3,4,6), to the saturation boundary as determined by Huber and Ely (1991). These adjusted thermal conductivities are then fit to a simple polynomial in temperature given by

$$\lambda_{sl} = 2.1099 \times 10^{-1} - 3.9431 \times 10^{-4} T - 1.2983 \times 10^{-7} T^2, \quad (8)$$

where the saturated liquid thermal conductivity λ_{sl} is in $\text{W m}^{-1} \text{K}^{-1}$ and T is in K. Deviations between the available saturated liquid thermal conductivity data and this correlation are shown in Figure 5. Good agreement is found with all of the available data sets from 240 to 300 K. The data of Ross et al. (1990) and Ruvinski et al.

(1990) are increasingly higher than our data as the critical temperature is approached for temperatures above 300 K. This could be due to free convection. The surface correlation of eqns. (2-6) is about 3% lower than our data at 369 K.

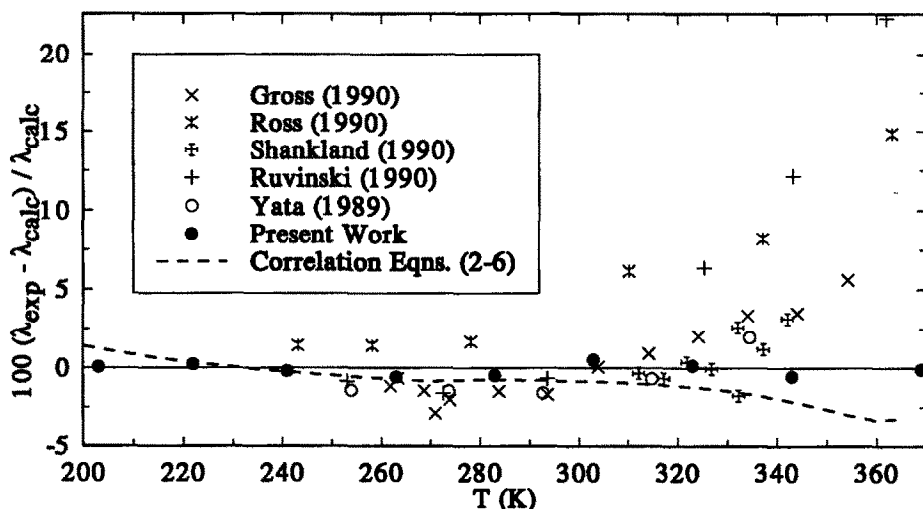


Fig. 5. Deviations between the experimental data and eqn. (8) for the saturated liquid thermal conductivity of R134a.

CONCLUSIONS

Extensive thermal conductivity measurements for the alternative refrigerant R134a are reported. Measurements in the liquid phase were made in the presence of a polarization voltage of 6 V to eliminate problems arising from the electrical properties of this polar fluid. These data are used to develop a thermal conductivity surface for R134a which covers the region from 200 to 390 K at pressures to 70 MPa with an uncertainty of $\pm 3.8\%$. This thermal conductivity surface reveals that the thermal conductivity critical enhancement becomes significant near the phase boundaries at temperatures above 350 K. Correlations are provided for the saturated vapor and liquid thermal conductivities of R134a which fit our data within $\pm 1\%$ below 350 K. In general, good agreement is found with the other available data for R134a in the dilute gas and along the saturated-vapor and saturated-liquid phase boundaries.

ACKNOWLEDGEMENTS

The financial assistance of the United States Environmental Protection Agency is gratefully acknowledged.

REFERENCES

- Fisher, D. A., Hales, C. H., Filkin, D. A., Ko, M. K. W., Sze, N. D., Connell, P. S., Wuebbles, D. J., Isaksen, I. S. A., and Stordal, F., 1990a. Model calculations of the relative effects of CFCs and their replacements on stratospheric ozone. *Nature* 344: 508-512.
- Fisher, D. A., Hales, C. H., Wang, W. C., Ko, M. K. W., and Sze, N. D., 1990b. Model calculations of the relative effects of CFCs and their replacements on global warming. *Nature* 344: 513-516.
- Gross, U., Song, Y. W., Kallweit, J., and Hahne, E., 1990. Thermal conductivity of saturated R123 and R134a. I.I.F. - I.I.R. Meeting, Commission B1, Tel Aviv, Israel.
- Huber, M. L. and Ely, J. F., 1991a. A predictive extended corresponding states model for pure and mixed refrigerants including a new equation of state for R134a. *Int. J. Refrig.*, submitted.
- Huber, M. L. and Ely, J. F., 1991b. Prediction of viscosity of refrigerants and refrigerant mixtures. Paper presented at 11th Symposium on Thermophysical Properties, Boulder, CO, Submitted to *Fluid Phase Equilibria*.
- Nieto de Castro, C. A., Dix, M., Fareleira, J. M. N. A., Li, S. F. Y., Wakeham, W. A., 1989. Thermal conductivity of chlorobenzene at pressures up to 430 MPa. *Physica* 156A: 534-546.
- Olchowy, G. A. and Sengers, J. V., 1988. Crossover from singular to regular behavior of the transport properties of fluids in the critical region. *Phys. Rev. Lett.* 61: 15-18.
- Perkins, R. A., Roder, H. M., and Nieto de Castro, C. A., 1991. A high temperature transient hot-wire thermal conductivity apparatus for fluids. *J. Res. Nat. Inst. Stand. and Tech. (U.S.)* 96: 247-269.
- Petersson, B. and Thorsell, H., 1990. Comparison of the refrigerants HFC 134a and CFC 12. *Int. J. Refrig.* 13: 176-180.
- Prather, M. J. and Watson, R. T., 1990. Stratospheric ozone depletion and future levels of atmospheric chlorine and bromine. *Nature* 344: 729-734.
- Roder, H. M., 1981. A transient hot wire thermal conductivity apparatus for fluids. *J. Res. Nat. Bur. Stand. (U.S.)* 86: 457-493.
- Ross, M., Trusler, J. P. M., Wakeham, W. A., and Zalaf, M., 1990. Thermal conductivity of R134a over the temperature range 240 to 373 K. I.I.F. - I.I.R. Meeting, Commission B1, Tel Aviv, Israel.
- Ruvinski, G. Y., Larrenchenko, G. K., and Ilyushenko, S. V., 1990. Thermophysical properties of R134a. *Kholodiln. Tekh.* 7: 20-26.
- Shankland, I. R., 1990. Transport properties of CFC alternatives. AIChE Spring National Meeting, Orlando, Florida.
- Tang, S., Jin, G. X., and Sengers, J. V., 1991. Thermodynamic properties of 1,1,1,2-tetrafluoroethane (R134a) in the critical region. *Int. J. Thermophys.* 12: 515-540.
- Yata J., Kawashima, C., Hori, M., and Minamiyama T., 1989. Thermal conductivity of R123 and R134a in liquid phase. In: *Proc. of the Second Asian Thermophysical Properties Conference*, pp. 201-205.