A Correlation of the Existing Viscosity and Thermal Conductivity Data of Gaseous and Liquid Ethane

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Data for the viscosity and thermal conductivity coefficients of ethane have been evaluated and represented by an empirical function. Tables of values have been prepared for the range 200–500 K, for pressure to 75 MPa ($\approx$ 750 atm). The tables include an estimate of the anomalous contribution to the thermal conductivity in the neighborhood of the critical point. The estimated uncertainties of the tabular values are ±5% and ±8% for the viscosity and thermal conductivity coefficient, respectively.

Key words: Critical point enhancement; data evaluation; ethane; thermal conductivity coefficient; viscosity coefficient.

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Nomenclature

T	temperature
p	pressure
K_T	compressibility
ρ	mass density
η	viscosity coefficient
η_0	dilute gas viscosity
η_1	viscosity first density correlation
$\Delta\eta$	excess viscosity
$\Delta\eta'$	dense gas and liquid viscosity
$\Delta\eta_c$	critical region excess viscosity
j_i $(i=1,7)$, E	viscosity equation parameters

$GV(i)$ $(i=1,9)$	dilute gas viscosity equation parameters
λ	thermal conductivity coefficient
λ_0	dilute gas thermal conductivity
λ_1	thermal conductivity first density correction
$\Delta\lambda$	excess thermal conductivity
$\Delta\lambda'$	dense gas and liquid thermal conductivity
$\Delta\lambda_c$	critical region excess thermal conductivity
k_i $(i=1,7)$, D	thermal conductivity equation parameters
$GT(i)$ $(i=1,9)$	dilute gas thermal conductivity equation parameters
M	molecular weight
N	Avogadro constant
k	Boltzmann constant
Φ	intermolecular pair potential
$m, \gamma', \sigma, r_m, d, \epsilon$	potential parameters
A, B, C, F	first density correction equation parameters
θ	viscosity and thermal conductivity equation variable
$*$	reduced variable superscript
c	critical point variable subscript
x_0, β, E_1, E_2, δ, γ	scaling parameters for the compressibility in the critical region
R	length parameter in the critical point equation
μ	chemical potential
A'	viscosity critical region parameter

1. Introduction

In reference [1][1] we set up a procedure to evaluate and represent the viscosity coefficient (η) and the thermal conductivity coefficient (λ) of simple fluids which has been applied to argon (with krypton and xenon), oxygen and nitrogen [1], and to methane [2, 3]. The object of this work is to include ethane; specifically to present tables of values of the transport coefficients covering a broad range of experimental conditions.

Several correlations of the ethane transport coefficients have been published [4]. Most, however, are restricted to one coefficient and most cover a limited experimental range. One of the difficulties is that the data base cannot be considered satisfactory by comparison with those of other simple fluids, such as the fluids studied in references [1–3]. For example, there are some gaps in the data coverage and the majority of the data available was published more than ten years ago. Data cannot, of course, be judged solely by their publication date, but it is generally accepted that much of the older data for many simple fluids are suspect. (In the last ten years or so, the conventional experimental procedures (e.g., the capillary flow and oscillating disc methods for the viscosity, and the hot wire and parallel plate methods for the thermal conductivity) have been re-examined and new techniques and modifications have been proposed [5].)

In summary, we do not think it possible to present authoritative tables, with a significant assessment of accuracy, until more, and more accurate, data are available. However there is considerable technical interest in ethane at this time and it was felt worthwhile to present tables of both the viscosity and the thermal conductivity coefficients over a wide experimental range. Guidelines for work which would lead to improved tables are suggested.

In reference [1], criteria for evaluating data in the literature were discussed, and an equation for the viscosity and thermal conductivity coefficient was proposed. This paper will follow closely the format of reference [1], so the criteria and the correlating equations will be used here with only minimal comments.

2. Correlating Equations

The correlation for ethane is based on the behavior of the transport coefficients with respect to temperature (T) and density (ρ) according to the equations

$$\eta(\rho, T) = \eta_0(T) + \eta_1(T)\rho + \Delta\eta'(\rho, T) + \Delta\eta_c(\rho, T), \tag{1}$$

$$\lambda(\rho, T) = \lambda_0(T) + \lambda_1(T)\rho + \Delta\lambda'(\rho, T) + \Delta\lambda_c(\rho, T), \tag{2}$$

for the viscosity and thermal conductivity, respectively. In these equations, $\eta_0(T)$ and $\lambda_0(T)$ are the dilute gas values; $\eta_1(T)$ and $\lambda_1(T)$ represent first density corrections for the moderately dense gas; while $\Delta\eta'(\rho, T)$ and $\Delta\lambda'(\rho, T)$ are remainders. The term $\eta_1(T)$ is given by the empirical expression

$$\eta_1(T) = A + B\,[C - \ln\,(T/F)]^2, \tag{3}$$

and similarly for $\lambda_1(T)$. The coefficients A, B, C and F can be found from a fit of data, but we set $F = \epsilon/k$ where ϵ is the energy parameter of the methane pair potential function and k is Boltzmann's constant. See section 3.

The terms $\Delta\eta'(\rho, T)$ and $\Delta\lambda'(\rho, T)$ are expressed empirically by the relations

$$\Delta\eta'(\rho, T) = E\exp\,[j_1 + j_4/T]\ \{\exp\,[\rho^{0.1}(j_2 + j_3/T^{3/2}) + \theta\rho^{0.5}(j_5 + j_6/T + j_7/T^2)] - 1.0\}, \tag{4}$$

and

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[1] Figures in brackets indicate literature references.

$$\Delta\lambda'(\rho,T)=D\exp\left[k_1+k_4/T\right]\{\exp\left[\rho^{0.1}(k_2+k_3/T^{3/2})+\theta\rho^{0.5}(k_5+k_6/T+k_7/T^2)\right]-1.0\}. \quad (5)$$

The parameter θ is included to account specifically for the high density behavior of the transport coefficients and is a function of the density with respect to the critical density, ρ_c:

$$\theta=(\rho-\rho_c)/\rho_c. \quad (6)$$

The coefficients, E, D, j_1 . . . j_7, k_1 . . . k_7, are to be obtained from experimental data.

Finally, equations (1) and (2) include the terms $\Delta\eta_c(\rho, T)$ and $\Delta\lambda_c(\rho, T)$, respectively, to account for the known enhancement of the coefficients in the vicinity of the critical point, see section 3.3.

As the form of the equations suggest, the transport coefficients are correlated and evaluated by examining their behavior with respect to density: thus for the viscosity, (a) we first evaluate the dilute gas and (b), with the critical region excluded, the experimental quantity $(\eta_{\mathrm{exp}}(\rho, T) - \eta_0(T))$ is identified with the terms $\eta_1(T)\rho + \Delta\eta'(\rho, T)$. Similarly for the thermal conductivity. The critical point behavior is treated separately.

2.1. The Equation of State

Since the correlation of the transport coefficients requires temperature-density coordinates, but the majority of data are reported in temperature-pressure coordinates, an accurate equation of state is essential. The equation of state for ethane used here was derived by Goodwin and discussed in reference [6].

3. Data

Our search of the literature produced the following papers reporting experimental measurements for the transport coefficients of ethane: viscosity, references [7–21], thermal conductivity, references [10], [13], [22–30].

Criteria for selecting data for correlation are discussed in section 2 of reference [1] and the ethane measurements were evaluated according to these criteria as far as possible. For example, it was pointed out that a plot of the excess function $\Delta\eta$ or $\Delta\lambda$ (defined as $\eta_{\mathrm{exp}}(\rho, T)-\eta_0(T)$ and $\lambda_{\mathrm{exp}}(\rho, T)-\lambda_0(T)$, respectively) versus density leads to a good first guess as to the precision and internal consistency of a given data set; it is a convenient format to compare different data sets; the plot also allows one to judge if the qualitative behavior of the coefficients for ethane is consistent with that of other simple fluids.

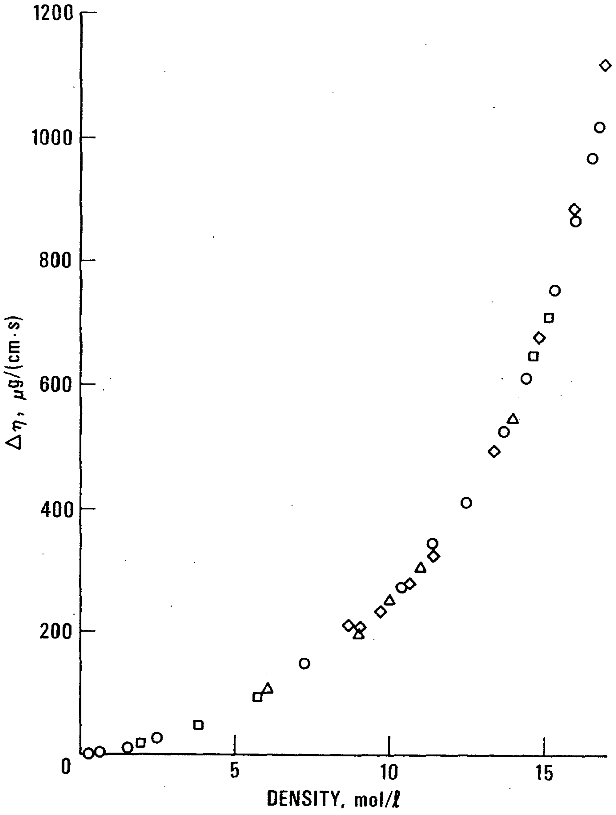

FIGURE 1. Plot of the excess viscosity coefficient versus density. O [7], ◇ [19], △ [8], □ [20].

We constructed figures 1 and 2 for the excess functions of ethane. Dilute gas data were represented by the empirical function discussed in section 3.1. Based on the corresponding behavior of simple fluids other than ethane (Ar, N_2, O_2, CO_2, F_2, H_2, CH_4, etc.) one would expect that both $\Delta\eta$ and $\Delta\lambda$ for ethane would be essentially temperature independent at a given density. (See figure 1 of reference [1], however.) The plot for the excess viscosity coefficient for several temperatures, figure 1, is in fact a reasonably smooth curve, but the plot for the excess thermal conductivity coefficient shows considerable scatter.

The behavior of the excess thermal conductivity coefficient suggests that much of this data is of questionable quality.

In summary, the data base for this correlation is references [7–13], [15], [19] and [20] for the viscosity, and references [13], [22–27], and [30] for the thermal conductivity. Equal weight was given to the measurements reported in these sources.

3.1. The Dilute Gas

It is convenient to consider the dilute gas, the dense gas and liquid, and the critical region separately, as suggested by equations (1) and (2).

Viscosity Coefficient

Data from references [7–15] were fitted to the empirical function found suitable in our previous work [1, 2]:

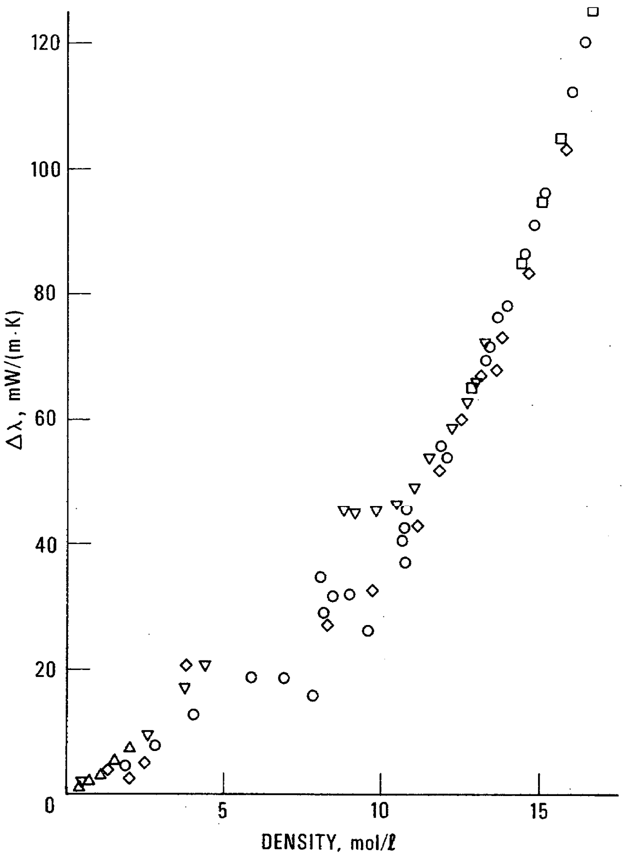

FIGURE 2. Plot of the excess thermal conductivity coefficient versus density. ▽ [25–27], O[22], △ [23], ◇ [30], □, saturated liquid values, see text, section 3.2.

$$\eta_0 = GV(1)T^{-1} + GV(2)T^{-2/3} + GV(3)T^{-1/3} + GV(4) + GV(5)T^{1/3} + GV(6)T^{2/3} + GV(7)T + GV(8)T^{4/3} + GV(9)T^{5/3}. \tag{7}$$

Values of the coefficients, $GV(1) \ldots GV(9)$, are listed in table 1 and a percent deviation plot is shown in figure 3. In this figure, and in subsequent figures, percent deviation is defined as

$$\frac{\eta(\text{expt}) - \eta(\text{calc})}{\eta(\text{expt})} \times 100. \tag{8}$$

Of the data fitted, those from reference [15] are judged to be the most accurate with an estimate of inaccuracy (uncertainty) of ± 0.5% (see the discussion in reference [1]). However, only two values at room temperature are reported. An objective assessment of the uncertainty in the data from the other authors is difficult since details of the experiments are often not available; some of the data have been extrapolated to lower pressures; the data of reference [11] can be expected to be slightly in error based on our analysis of the apparatus used [31]. It turns out, however, as can be seen in figure 3, that the data of all authors are within ±2%. Overall, we estimate that values of the viscosity coefficient generated from equation (3) are accurate to ±4%.

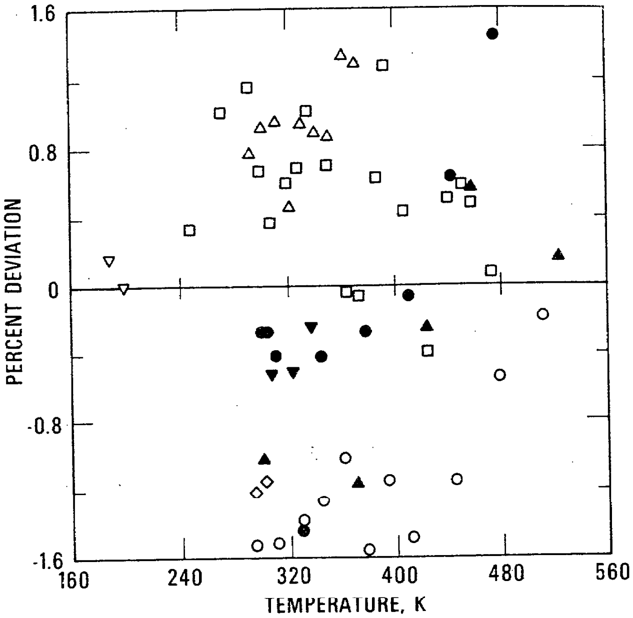

FIGURE 3. Deviation plot between dilute gas viscosity data and values calculated from equation (7): O[7], ● [8], ▽ [10], □ [9], ◇ [15], ▼ [13], △ [12], ▲ [11].

Thermal Conductivity Coefficient

Dilute gas thermal conductivity data from references [13], [22–27], [30] were fitted to equation (9):

$$\lambda_0 = GT(1)T^{-1} + GT(2)T^{-2/3} + GT(3)T^{-1/3} + GT(4) + GT(5)T^{1/3} + GT(6)T^{2/3} + GT(7)T + GT(8)T^{4/3} + GT(9)T^{5/3}, \tag{9}$$

which is of the same form as the dilute gas viscosity equation (7). Values of the coefficients, $GT(1) \ldots GT(9)$ are listed in table 1. A deviation curve is shown as figure 4. The thermal conductivity data cannot be considered to be very accurate (cf., figure 2); there is scatter between data sets and the internal consistency is often poor for a given data set. An estimate of inaccuracy of the values obtained from equation (9) is ±6%.

Theoretical Calculation of the Dilute Gas Transport Coefficients

In our previous work [32], it has been shown that kinetic theory and statistical mechanics can be useful aids to assess the consistency and accuracy of data. For several gases, carbon dioxide for example [32], it was possible to show that the independently measured properties, the viscosity and thermal conductivity coefficients, the thermal diffusion factor, and the equilibrium pressure and dielectric virial coefficients, were mutually consistent. The potential function required to carry out the calculations was the m-6-8 discussed extensively

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TABLE1.  DILUTE GAS PARAMETERS FOR EQUATIONS
         (7) AND (9).  UNITS: TEMPERATURE IN
         K, VISCOSITY IN MICRO-G/(CM*S) AND
         THERMAL CONDUCTIVITY IN MILLI-W/(M*K)


           GV(1)=-.1987898689E+08
           GV(2)= .1265234425E+08
           GV(3)=-.2682486613E+07
           GV(4)= .1518198258E+06
           GV(5)= .2421166581E+04
           GV(6)= .5847272516E+04
           GV(7)=-.1547974517E+04
           GV(8)= .1379214849E+03
           GV(9)=-.4308581804E+01


           GT(1)=-.1098251238E+08
           GT(2)= .9388820895E+07
           GT(3)=-.2962175792E+07
           GT(4)= .3125105169E+06
           GT(5)= .4546887452E+05
           GT(6)=-.1730924346E+05
           GT(7)= .2128092919E+04
           GT(8)=-.1237826311E+03
           GT(9)= .2869768987E+01
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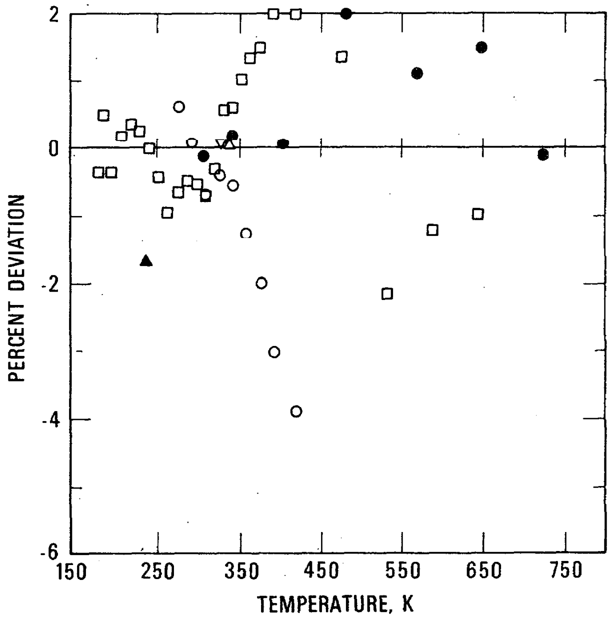

FIGURE 4. Deviation plot between dilute gas thermal conductivity data and values calculated from equation (9): O [30], ∇ [23], ▲ [24], △ [13], □ [25,27], ● [22].

in references [1, 2], [32] and elsewhere[2]. Following our previous work therefore, we have obtained m-6-8 parameters for ethane from the viscosity data which are listed in table 2.

TABLE 2. m-6-8 potential function [1] parameters and critical point parameters for ethane

Critical point constants
$T_c = 305.4$ K $\rho_c = 0.2015$ g/cm^3 (6.70 mol/l) $P_c = 4.8755$ MPa (48.117 atm) $M = 30.07$
Parameters for equation (15)
$E_1 = 2.1$ $E_2 = 0.287$ $x_0 = 0.166$ $\beta = 0.355$ $\gamma = 1.190$ $\delta = 4.352$
m-6-8 parameters
$\epsilon/k = 240.0$ K $\sigma = 4.38 \times 10^{-10}$ m $r_m = 4.88 \times 10^{-10}$ m $\gamma' = 3.0$ $m = 11$

3.2. The Dense Gas and Liquid

Having values for $\eta_0(T)$, and with $\Delta\eta^c(\rho, T)$ set equal to zero, dense gas and liquid data were fitted by the method of least squares [1] to the terms $\eta_1(T)\rho + \Delta\eta'(\rho, T)$ of equation (1).

The data selected were those of references [7], [8], [19] and [20]. Equal weight was given to the data points. The accuracy of the data was judged to be ±5%. Values of the coefficients A, B, C, F, and $J_1 \ldots J_7$ are given in table 3.

Similarly for the thermal conductivity coefficient: the data selected was extracted from references [22], [23], [25–27] and [30]. As noted for figure 2, much of the data must be regarded as suspect. It is difficult to justify anything but to give equal weight to all data points.

One of the drawbacks of the thermal conductivity data base is that no values for the saturated liquid are available, but we have found by experience that equation (5) for $\Delta\lambda'$ requires data at, or close to, saturation if the equation is to represent properly the dense liquid. To ensure, therefore, that equation (5) is well-behaved at low temperatures and high densities, we considered dummy saturated liquid points obtained from the excess function graph, figure 2.

Sample deviation curves are given in figures 5–8 which indicate that the data have been fitted to within their estimated accuracy.

3.3. The Critical Region

Thermal Conductivity

As remarked, the quantity $\Delta\lambda_c(\rho, T)$ of equation (2) represents the anomalous behavior of the thermal

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[2] The m-6-8 potential is given by the expression

$$\frac{\Phi(r^*)}{\epsilon} = \frac{1}{m-6}[6 + 2\gamma'](d/r^*)^m - \frac{1}{m-6}[m - \gamma'(m-8)]\,(d/r^*)^6 - \gamma'(d/r^*)^8,$$

where $d = r_m/\sigma$ and $r^* = r/\sigma$. The distance parameters σ and r_m, and the energy parameter, ϵ, are defined by the relationships $\Phi(r_m) = -\epsilon$ and $\Phi(\sigma) = 0$ while γ' is a parameter representing inverse eighth attraction in the potential.

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TABLE3.  PARAMETERS FOR EQUATIONS (3)-(5).
         UNITS: TEMPERATURE IN K, VISCOSITY
         IN MICRO-G/(CM*S) AND THERMAL CON-
         DUCTIVITY IN MILLI-W/(M*K).

VISCOSITY
EQUATION 3       A=-3.911393979
                 B=4.202777039
                 C=1.12
                 F=305.4
EQUATION 4       E=1.0
                 J1=-.1005824181E+02
                 J2= .3708447683E+00
                 J3= .1730063144E+02
                 J4= .1214721698E+05
                 J5=-.3715982490E+04
                 J6= .1934946036E+03
                 J7= .8669596196E+02

THERMAL CONDUCTIVITY
EQUATION 3       A=.20556824905
                 B=.91610917354
                 C=1.12
                 F=305.4

EQUATION 5       D=1.0
                 K1=-.94345320091E+01
                 K2= .19662879028E+01
                 K3= .13089936918E+02
                 K4= .14011587268E+06
                 K5=-.17755038676E+05
                 K6= .13738492230E+04
                 K7=-.91049943375E+03
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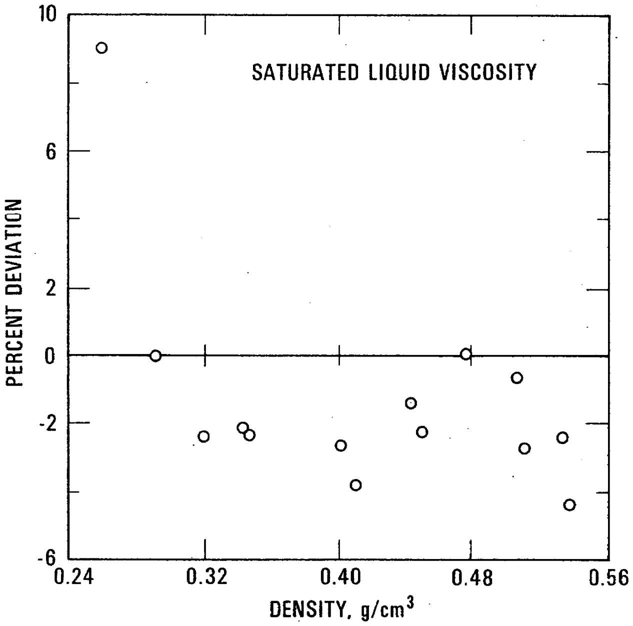

FIGURE 5. Deviation plot for the viscosity coefficient at saturated liquid boundary. Data from reference [19] compared to equation (1).

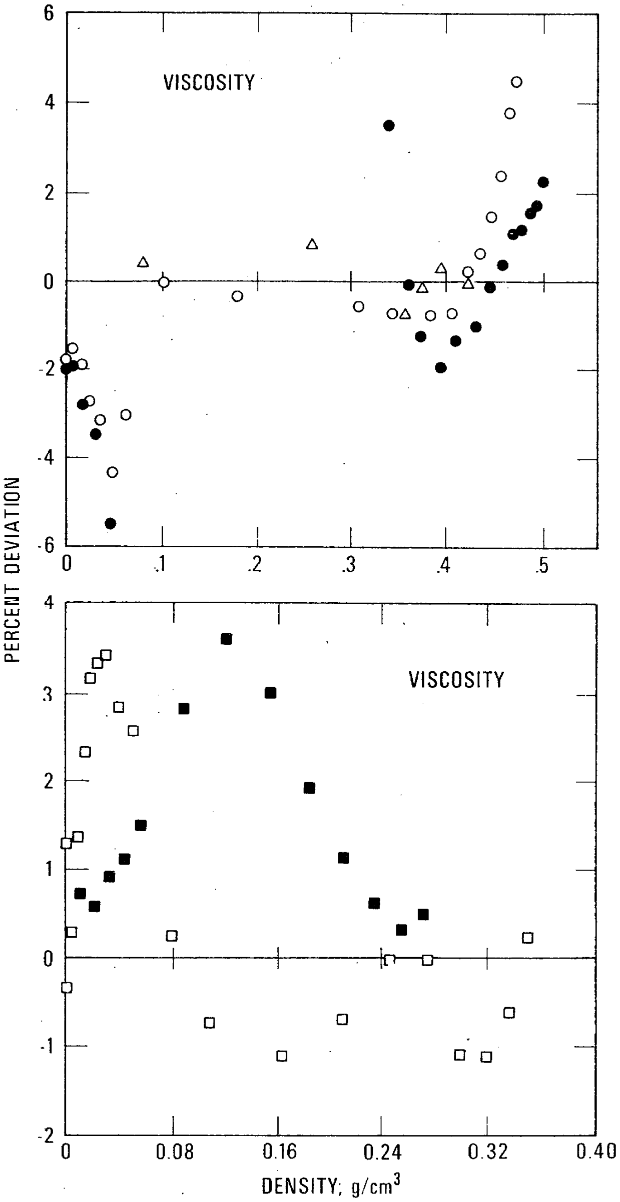

FIGURE 6. Deviation plots for the viscosity coefficient for several isotherms: top, ● [7] at 294 K, △ [8] at 326 K; ○ [7] at 327 K; bottom, ■ [8] at 478 K, □ [7] at 511 K.

conductivity coefficient in the neighborhood of the critical point. There is no doubt that $\Delta\lambda_c$ can contribute significantly to the value of the thermal conductivity coefficient and has to be included in a correlation [1]. Conductivity data, however, in the critical region for ethane are nonexistent, hence $\Delta\lambda_c$ is obtained by calculation. The procedure is discussed in section 3.2 of reference [1] and in reference [33].

According to reference [33],

$$\Delta\lambda_c(\rho, T) = \left(\frac{M}{\rho NkT}\right)^{1/2} \frac{kT^2}{6\pi\eta R} \left(\frac{\partial P}{\partial T}\right)_\rho^2 (K_T)^{1/2}$$

$$\exp(-18.66\ \tilde{\Delta}T^2)\exp(-4.25\ \tilde{\Delta}\rho^4), \qquad (10)$$

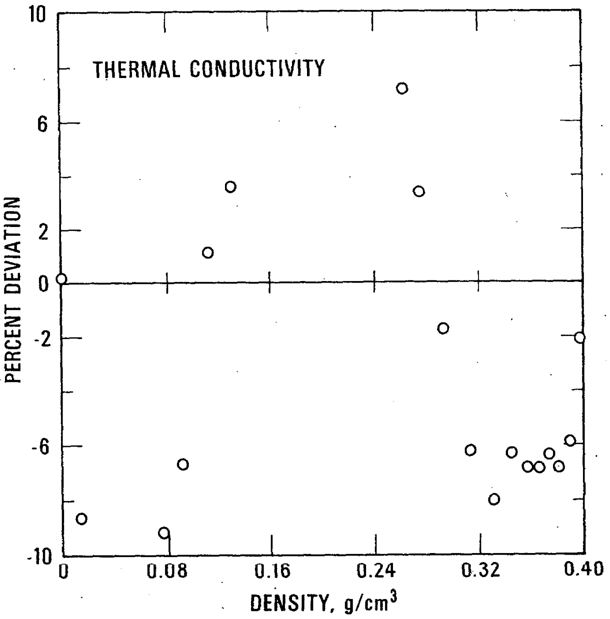

FIGURE 7. Deviation plots for the thermal conductivity coefficient at 315 K. Data from reference [26] compared to equation (2).

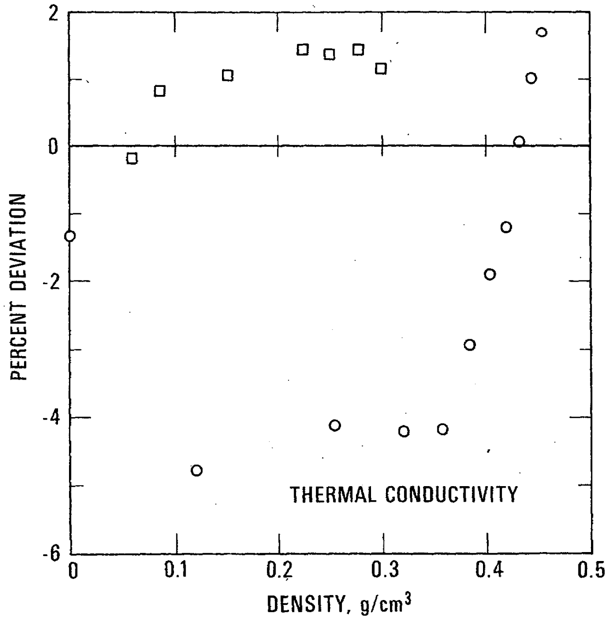

FIGURE 8. Deviation plot for the thermal conductivity coefficient at 649 K, □, and 406 K, O. Data from reference [22].

where

$$\tilde{\Delta}T = |T - T_c|/T_c; \ \tilde{\Delta}\rho = |\rho - \rho_c|/\rho_c, \qquad (11)$$

with T_c and ρ_c the critical temperature and density, respectively. In equation (10), k is Boltzmann's constant, N is Avogadro's constant, $K_T = \rho^{-1}(\partial\rho/\partial P)_T$ (the compressibility), R is a length parameter and M is the molecular weight. R is given by:

$$R = r_m^{5/2}\left(\frac{N\rho}{T^*}\right)^{1/2}\left(\frac{2\pi}{3}\right)\left[\frac{m-\gamma'(m-8)}{m-6}+\frac{\gamma'}{3}\right]^{1/2}, \qquad (12)$$

where $T^* = T/(\epsilon/k)$, m, γ', r_m and ϵ/k are the m-6-8 parameters of table 2.

One can see that the calculation of $\Delta\lambda_c$ at a given density and temperature requires the viscosity, the derivative $(\partial P/\partial T)_\rho$, and K_T. The viscosity is obtained from our correlation, and $(\partial P/\partial T)_\rho$ and K_T can be obtained from the equation of state [6]. However, it turns out that while the determination of $(\partial P/\partial T)_\rho$ presents no real difficulty, the determination of K_T does: it is now well-known that the classical, analytical, equations of state cannot describe the large compressibilities in the critical region. The equation of Goodwin used here, however, is nonanalytic and could, in principle, be used for K_T. Nevertheless, we prefer to be consistent with our previous work and introduce the scaled equation of state:

$$\rho^2 K_T = \frac{\rho_c}{P_c}|\tilde{\Delta}\rho|^{1-\delta}\left[h(x) - \frac{x}{\beta}h'(x)\right]^{-1}, \qquad (13)$$

where $h'(x) \equiv dh(x)/dx$. The derivation of equation (13) is based on the observation that the asymptotic behavior of various thermodynamic properties can be described in terms of power laws when the critical point is approached along specific paths in the $\tilde{\Delta}T - \tilde{\Delta}\rho$ plane. For example, the density along the gas and liquid branch of the coexistence curve varies asymptotically as $|\tilde{\Delta}\rho| \propto |\tilde{\Delta}T|^{\beta}$; the chemical potential $\mu(\rho, T)$ along the critical isotherm varies as $\mu(\rho, T_c) - \mu(\rho_c, T_c) \propto |\tilde{\Delta}\rho|^{\delta}$; the compressibility K_T and specific heat c_p at constant pressure vary along the critical isochore as $|\tilde{\Delta}T|^{-\gamma}$. The quantity x is given by the ratio:

$$x = \tilde{\Delta}T/|\tilde{\Delta}\rho|^{1/\beta}, \qquad (14)$$

and $h(x)$ is a function:

$$h(x) = E_1\left(\frac{x+x_0}{x_0}\right)\left[1 + E_2\left(\frac{x+x_0}{x_0}\right)^{2\beta}\right]^{(\gamma-1)/2\beta}. \qquad (15)$$

This equation contains the critical parameters ρ_c and T_c (through the definition of x), two critical exponents β and $\gamma[=\beta(\delta-1)]$, and three constants x_0, E_1 and E_2. Values of the constants and exponents are listed in table 2.

As an example, the total thermal conductivity coefficient $\lambda(\rho, T)$ has been calculated at three temperatures: 400 K, 310 K and 305.7 K. The appropriate excess function $\Delta\lambda[=\lambda(\rho, T) - \lambda_0(T)]$ has been plotted versus density in figure 9. It is seen that the influence of the critical point increases significantly the value of $\Delta\lambda$.

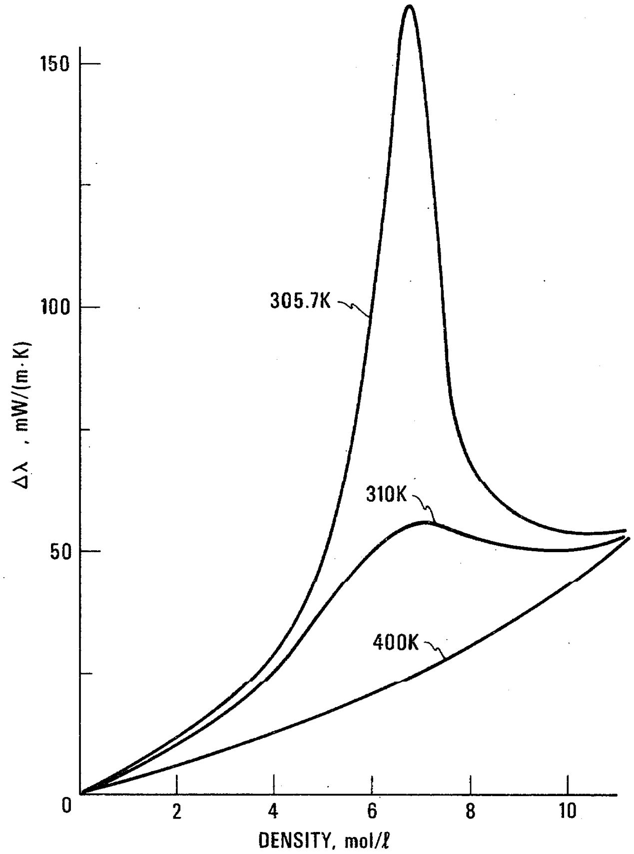

FIGURE 9. Plot of the calculated excess thermal conductivity coefficient, using equation (10), at 305.7 K, 310 K, and 400 K.

Viscosity Coefficient

Although it has been suspected for a long time that the viscosity coefficient of a pure fluid displays anomalous behavior in the critical region, the magnitude and quantitative features of the anomaly are still under investigation but it is generally conceded that any anomalous behavior of the viscosity is much weaker than the corresponding behavior of the thermal conductivity. Recently, however, Strumpf, Collings and Pings investigated experimentally the viscosity of ethane in the vicinity of the critical point [21]. They report an anomalous increase in the viscosity of about 16% if $\underset{\sim}{\Delta T} \leq 0.0025$ and $\underset{\sim}{\Delta\rho} \leq 0.25$. Further, the results agree with theoretical predictions [34] that $\Delta\eta_c/\eta(\text{back}) = A' \ln \underset{\sim}{\Delta T}$, where η(back) is the viscosity in the absence of anomaly, and A' is a constant which has a numerical value of approximately 0.034. There seems little doubt that Strumpf, Collings, and Pings have verified quantitatively the existence of a critical point anomaly in the viscosity of ethane. Unfortunately, from our viewpoint, the absolute values of the coefficients are uncertain. It turns out that the coefficients away the critical point differ systematically by 5–10% from those of Carmichael and Sage [8], and of the other authors considered here. The latter results are higher at a given temperature and density. Possible reasons for the discrepancies are discussed in reference [21].

Accordingly, in view of the discrepancies, and since the data of reference [21] cover a limited experimental region, the data were excluded from the correlation.

4. Tables of Values

The viscosity and thermal conductivity coefficients of ethane have been calculated for 200–300 K for pressures up to 50 MPa ($\approx$500 atm) and from 300–500 K for pressures to 75 MPa. Tabular values are presented as tables 4 and 5. We ensured that an entry in the table would not require an extrapolation beyond the range of data, with the exception that the low temperature-high pressure thermal conductivity coefficients required our generated saturated liquid values from the excess function. Gaps in the tables at low temperatures indicate that these *P-T* points correspond to densities exceeding 17 mol/l: the upper density limit for the data. For convenience saturated liquid values have been listed separately as table 6. (The tables contain more significant figures than the accuracy of the data warrant. The extra figures are given to facilitate reproduction and interpolation of the tables.)

4.1. Uncertainty of the Tables

We have been able to fit the data to within their estimated accuracy. The tabular values are judged to have an uncertainty of ±5% for the viscosity coefficient and ±8% for the thermal conductivity coefficient. These estimates of uncertainty refer to an estimate of accuracy on a 2σ basis. Here σ is based on the following: the scatter of the experimental data, deviations between the data and our correlation, an assessment of the data according to the criteria of reference [1] and, finally, our experience of evaluating similar data for other simple fluids. Close to the critical point, the estimated uncertainties are increased to ±10% for the viscosity coefficient, and ±20% for the thermal conductivity coefficient.

5. Conclusion

The viscosity and thermal conductivity coefficient data for ethane over a wide temperature and pressure range have been represented by an empirical function. Tables of values have been prepared. Our assessment and evaluation of the results has been handicapped by lack of reliable data. A significant improvement requires (a) data for the dilute gas over a wide temperature range, e.g., about 200–1500 K, particularly for the viscosity coefficient, (b) viscosity data for the saturated liquid from the triple point (90.35 K) to 200 K, and (c) thermal conductivity data for the saturated liquid over the whole temperature range. It would also be helpful if the more recent techniques, e.g., those using the torsional oscillating crystal for the viscosity [1], and the transient hot wire method [2], could be applied to ethane.

TABLE 4. *Viscosity coefficient of ethane for various temperatures (K) and pressures (MPa). The units are μg/(cm·s)*

	P, MPa									
T, K	.1	.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0
200.	65.6									
205.	67.2									
210.	68.6									
215.	70.0	1173.6	1179.9	1186.1	1192.3	1198.5	1204.6	1210.7	1216.7	1228.7
220.	71.4	1109.0	1115.[illegible]	1121.7	1128.0	1134.2	1140.3	1146.4	1152.5	1164.5
225.	72.7	74.5	1054.4	1060.8	1067.2	1073.5	1079.7	1085.9	1092.0	1104.1
230.	74.1	75.9	996.5	1003.0	1009.5	1015.9	1022.3	1028.5	1034.8	1047.1
235.	75.5	77.2	941.2	947.9	954.6	961.1	967.6	974.1	980.4	992.9
240.	76.8	78.5	888.1	895.1	902.0	908.8	915.4	922.0	928.6	941.4
245.	78.2	79.9	82.4	844.2	851.4	858.4	865.4	872.2	878.9	892.1
250.	79.7	81.2	83.7	794.8	802.4	809.8	817.0	824.2	831.2	844.9
255.	81.1	82.6	85.0	746.6	754.6	762.5	770.1	777.7	785.0	799.5
260.	82.5	84.1	86.4	89.4	707.6	716.1	724.3	732.3	740.1	755.1
265.	84.0	85.5	87.7	90.6	660.9	670.1	679.1	687.7	696.1	712.1
270.	85.5	86.9	89.1	91.8	95.5	624.0	633.9	643.4	652.6	669.9
275.	87.0	88.4	90.5	93.1	96.5	576.7	588.1	598.9	609.1	628.1
280.	88.5	89.9	91.9	94.4	97.6	102.0	540.3	553.1	564.8	586.3
285.	90.0	91.4	93.3	95.7	98.7	102.7	108.7	504.3	518.7	543.0
290.	91.5	92.8	94.8	97.1	99.9	103.6	108.7	117.5	460.4	499.6
295.	93.0	94.3	96.2	98.5	101.2	104.6	109.1	115.9	407.4	451.7
300.	94.5	95.8	97.7	99.8	102.4	105.6	109.7	115.4	124.7	395.9

	P, MPa									
T, K	6.0	7.0	8.0	9.0	10.0	15.0	20.0	30.0	40.0	50.0
220.	1176.4	1188.1	1199.7	1211.1	1222.5					
225.	1116.1	1127.9	1139.5	1151.0	1162.3	1217.0				
230.	1059.2	1071.0	1082.8	1094.3	1105.7	1160.4	1212.3			
235.	1005.2	1017.3	1029.1	1040.8	1052.2	1107.2	1158.9			
240.	953.9	966.2	978.2	990.0	1001.6	1056.9	1108.7	1204.3		
245.	905.0	917.5	929.8	941.6	953.6	1009.4	1061.3	1156.5		
250.	858.1	871.0	883.6	895.9	907.9	964.4	1016.5	1111.5		
255.	813.1	826.4	839.4	852.0	864.2	921.6	974.1	1068.9	1154.0	
260.	769.6	783.5	796.9	809.8	822.5	880.9	933.8	1028.7	1114.0	
265.	727.4	741.9	755.9	769.3	782.3	842.1	895.6	990.6	1075.5	1153.6
270.	686.2	701.6	716.2	730.2	743.7	805.1	859.2	954.5	1039.0	1116.4
275.	645.7	662.1	677.6	692.4	706.5	769.6	824.6	920.3	1004.4	1081.1
280.	605.6	623.4	640.0	655.6	670.3	735.6	791.5	887.7	971.6	1047.7
285.	565.6	585.1	603.0	619.6	635.2	702.9	759.9	856.7	940.4	1016.0
290.	524.9	546.8	566.4	584.3	600.9	671.4	729.6	827.2	910.7	985.9
295.	482.8	508.1	530.8	549.5	567.4	641.2	700.7	799.1	882.5	957.2
300.	438.0	468.5	493.4	515.8	534.4	612.0	673.3	772.3	855.7	929.9

TABLE 4. Viscosity coefficient of ethane for various temperatures (K) and pressures (MPa). The units are μg/(cm•s)—Continued

				P, MPa						
T, K	.1	.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0
300.	94.5	95.8	97.7	99.8	102.4	105.6	109.7	115.4	124.7	395.9
310.	97.5	98.8	100.6	102.6	105.0	107.9	111.4	115.8	121.9	149.5
320.	100.5	101.7	103.4	105.4	107.6	110.2	113.3	117.1	121.8	136.5
330.	103.5	104.7	106.3	108.1	110.2	112.6	115.4	118.7	122.6	133.5
340.	106.4	107.6	109.1	110.9	112.9	115.1	117.7	120.6	124.0	132.9
350.	109.3	110.4	111.9	113.6	115.5	117.6	119.9	122.6	125.7	133.2
360.	112.2	113.2	114.7	116.3	118.1	120.1	122.3	124.7	127.5	134.2
370.	115.0	116.0	117.4	119.0	120.7	122.5	124.6	126.9	129.5	135.5
380.	117.8	118.8	120.1	121.6	123.2	125.0	127.0	129.1	131.5	137.0
390.	120.5	121.5	122.8	124.2	125.8	127.5	129.3	131.4	133.6	138.6
400.	123.2	124.2	125.4	126.8	128.3	129.9	131.7	133.6	135.7	140.4
410.	125.9	126.8	128.0	129.4	130.8	132.4	134.1	135.9	137.8	142.2
420.	128.5	129.4	130.6	131.9	133.3	134.8	136.4	138.1	140.0	144.1
430.	131.1	132.0	133.2	134.4	135.7	137.2	138.7	140.4	142.2	146.1
440.	133.7	134.6	135.7	136.9	138.2	139.6	141.1	142.6	144.3	148.0
450.	136.2	137.1	138.2	139.3	140.6	141.9	143.4	144.9	146.5	150.0
460.	138.7	139.5	140.6	141.7	143.0	144.3	145.6	147.1	148.6	152.0
470.	141.2	142.0	143.0	144.1	145.3	146.5	147.9	149.3	150.8	154.0
480.	143.6	144.3	145.3	146.4	147.6	148.8	150.1	151.4	152.9	156.0
490.	145.9	146.6	147.6	148.7	149.8	151.0	152.2	153.5	154.9	157.9
500.	148.1	148.9	149.8	150.8	151.9	153.1	154.3	155.6	156.9	159.8

				P, MPa						
T, K	6.0	7.0	8.0	9.0	10.0	15.0	20.0	30.0	50.0	75.0
300.	438.0	468.5	493.4	515.0	534.4	0.0	0.0	0.0	0.0	0.0
310.	324.8	382.0	417.9	445.9	469.4	556.5	0.0	0.0	0.0	0.0
320.	176.8	273.7	335.7	375.1	405.1	504.6	0.0	0.0	0.0	0.0
330.	152.5	192.5	251.7	303.2	341.6	456.2	528.6	0.0	0.0	0.0
340.	146.0	167.5	201.8	243.4	283.5	411.2	487.8	0.0	0.0	0.0
350.	143.6	158.4	180.0	208.6	240.4	370.2	450.5	561.3	0.0	0.0
360.	142.8	154.3	169.8	190.0	214.1	333.9	416.6	529.1	0.0	0.0
370.	142.9	152.4	164.5	179.8	198.2	303.2	386.8	499.7	0.0	0.0
380.	143.6	151.7	161.7	174.0	188.6	278.5	359.0	472.9	0.0	0.0
390.	144.6	151.8	160.4	170.6	182.6	259.5	335.5	448.5	0.0	0.0
400.	145.9	152.3	159.8	168.6	178.8	245.1	315.4	426.3	577.4	0.0
410.	147.3	153.1	159.9	167.6	176.5	234.2	298.5	406.3	555.7	0.0
420.	148.8	154.2	160.4	167.3	175.1	226.0	284.6	388.3	535.7	0.0
430.	150.5	155.5	161.1	167.4	174.4	219.7	273.1	372.2	517.2	0.0
440.	152.2	156.9	162.1	167.8	174.2	215.0	263.8	357.8	500.1	0.0
450.	154.0	158.3	163.2	168.5	174.4	211.4	256.1	345.1	484.3	0.0
460.	155.7	159.9	164.4	169.4	174.8	208.6	249.9	333.9	469.7	596.7
470.	157.6	161.5	165.7	170.4	175.5	206.6	244.7	323.9	456.2	581.2
480.	159.4	163.1	167.1	171.5	176.2	205.1	240.5	315.2	443.7	566.6
490.	161.1	164.7	168.5	172.7	177.1	204.1	237.0	307.6	432.1	552.9
500.	162.9	166.3	169.9	173.9	178.1	203.3	234.1	300.8	421.4	540.0

TABLE 5. Thermal conductivity of ethane for various temperatures (K) and pressures (MPa). The units are mW/(m•K)

					P, MPa					
T, K	.1	.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0
200.	12.78									
205.	13.17									
210.	13.56									
215.	13.97	145.23	145.77	146.31	146.85	147.38	147.91	148.43	148.95	149.98
220.	14.40	138.54	139.08	139.62	140.15	140.68	141.20	141.72	142.23	143.24
225.	14.83	17.10	133.17	133.70	134.24	134.76	135.29	135.80	136.32	137.33
230.	15.28	17.49	127.86	128.41	128.95	129.48	130.01	130.53	131.05	132.06
235.	15.74	17.89	123.03	123.59	124.15	124.69	125.23	125.76	126.29	127.32
240.	16.21	18.31	118.57	119.15	119.73	120.29	120.85	121.40	121.94	122.99
245.	16.69	18.73	20.65	114.98	115.59	116.18	116.76	117.33	117.89	118.99
250.	17.18	19.17	21.03	111.00	111.65	112.28	112.89	113.50	114.09	115.23
255.	17.68	19.61	21.42	107.14	107.83	108.51	109.17	109.82	110.44	111.66
260.	18.20	20.07	21.82	23.58	104.07	104.81	105.53	106.23	106.91	108.21
265.	18.72	20.54	22.24	23.91	100.27	101.10	101.91	102.68	103.42	104.83
270.	19.25	21.02	22.67	24.27	26.13	97.31	98.22	99.09	99.92	101.48
275.	19.79	21.51	23.11	24.65	26.38	93.34	94.40	95.40	96.34	98.09
280.	20.34	22.00	23.56	25.04	26.67	28.78	90.37	91.55	92.64	94.64
285.	20.90	22.52	24.02	25.46	27.00	28.89	31.86	87.50	88.80	91.10
290.	21.48	23.04	24.50	25.88	27.35	29.08	31.52	36.48	84.82	87.48
295.	22.05	23.57	24.99	26.32	27.72	29.33	31.44	34.85	80.85	83.87
300.	22.64	24.11	25.49	26.78	28.11	29.62	31.50	34.21	39.25	80.40

					P, MPa					
T, K	6.0	7.0	8.0	9.0	10.0	15.0	20.0	30.0	40.0	50.0
220.	144.24	145.22	146.19	147.15	148.09	0.00	0.00	0.00	0.00	0.00
225.	138.32	139.29	140.25	141.19	142.12	146.58	0.00	0.00	0.00	0.00
230.	133.06	134.03	134.99	135.93	136.85	141.27	145.38	0.00	0.00	0.00
235.	128.33	129.31	130.28	131.22	132.15	136.55	140.63	0.00	0.00	0.00
240.	124.02	125.03	126.01	126.97	127.90	132.33	136.40	143.77	0.00	0.00
245.	120.05	121.08	122.09	123.07	124.02	128.50	132.59	139.92	0.00	0.00
250.	116.34	117.41	118.45	119.46	120.44	125.00	129.12	136.46	0.00	0.00
255.	112.82	113.95	115.03	116.07	117.09	121.76	125.95	133.32	139.80	0.00
260.	109.45	110.63	111.77	112.86	113.92	118.74	123.01	130.45	136.93	0.00
265.	106.17	107.43	108.64	109.79	110.90	115.90	120.27	127.80	134.31	140.14
270.	102.93	104.29	105.58	106.81	107.98	113.20	117.69	125.34	131.89	137.73
275.	99.70	101.18	102.58	103.89	105.13	110.61	115.24	123.04	129.65	135.51
280.	96.43	98.07	99.59	101.01	102.34	108.11	112.91	120.88	127.56	133.45
285.	93.12	94.94	96.60	98.14	99.58	105.68	110.67	118.83	125.60	131.54
290.	89.76	91.79	93.61	95.28	96.83	103.31	108.50	116.88	123.76	129.74
295.	86.42	88.65	90.64	92.45	94.11	100.99	106.41	115.01	122.00	128.05
300.	83.18	85.59	87.73	89.67	91.44	98.72	104.37	113.22	120.33	126.45

TABLE 5. Thermal conductivity of ethane for various temperatures (K) and pressures (MPa). The units are mW/(m•K)—Continued

	P, MPa									
T, K	.1	.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0
300.	22.64	24.11	25.49	26.78	28.11	29.62	31.50	34.21	39.25	80.40
310.	23.85	25.23	26.53	27.73	28.96	30.29	31.86	33.86	36.68	51.35
320.	25.09	26.39	27.61	28.74	29.87	31.07	32.43	34.04	36.08	42.73
330.	26.37	27.60	28.75	29.80	30.85	31.94	33.14	34.49	36.11	40.61
340.	27.69	28.84	29.93	30.92	31.89	32.89	33.96	35.14	36.47	39.89
350.	29.05	30.13	31.16	32.09	32.99	33.92	34.88	35.92	37.06	39.81
360.	30.44	31.46	32.43	33.30	34.15	35.01	35.88	36.81	37.81	40.10
370.	31.86	32.83	33.75	34.57	35.37	36.16	36.97	37.80	38.69	40.66
380.	33.32	34.24	35.10	35.88	36.63	37.37	38.12	38.88	39.68	41.41
390.	34.82	35.68	36.50	37.24	37.94	38.64	39.33	40.04	40.76	42.31
400.	36.34	37.16	37.94	38.64	39.30	39.95	40.60	41.26	41.93	43.33
410.	37.89	38.67	39.41	40.07	40.70	41.31	41.92	42.54	43.16	44.44
420.	39.47	40.21	40.91	41.54	42.14	42.72	43.29	43.87	44.45	45.64
430.	41.07	41.78	42.45	43.04	43.61	44.16	44.70	45.25	45.79	46.90
440.	42.69	43.37	44.01	44.58	45.12	45.64	46.15	46.67	47.18	48.22
450.	44.34	44.98	45.59	46.14	46.65	47.15	47.64	48.12	48.61	49.58
460.	46.00	46.62	47.20	47.72	48.21	48.69	49.15	49.61	50.07	50.99
470.	47.68	48.27	48.83	49.33	49.79	50.25	50.69	51.13	51.56	52.44
480.	49.37	49.94	50.47	50.95	51.48	51.83	52.26	52.67	53.09	53.92
490.	51.08	51.62	52.14	52.59	53.02	53.44	53.84	54.24	54.64	55.43
500.	52.80	53.32	53.81	54.25	54.67	55.06	55.45	55.83	56.21	56.96

	P, MPa									
T, K	6.0	7.0	8.0	9.0	10.0	15.0	20.0	30.0	50.0	75.0
300.	83.18	85.59	87.73	89.67	91.44	0.00	0.00	0.00	0.00	0.00
310.	77.01	79.91	82.34	84.47	86.41	94.34	0.00	0.00	0.00	0.00
320.	58.30	72.47	76.94	79.69	81.89	90.27	0.00	0.00	0.00	0.00
330.	48.10	59.12	68.28	73.76	77.13	86.61	93.36	0.00	0.00	0.00
340.	44.79	51.62	59.19	65.77	70.90	83.18	90.16	0.00	0.00	0.00
350.	43.42	48.12	53.67	59.24	64.31	79.62	87.24	98.20	0.00	0.00
360.	42.95	46.45	50.58	55.02	59.39	75.78	84.40	95.76	0.00	0.00
370.	42.99	45.75	48.94	52.46	56.09	71.90	81.55	93.49	0.00	0.00
380.	43.38	45.64	48.21	51.04	54.04	68.44	78.71	91.36	0.00	0.00
390.	44.02	45.93	48.06	50.39	52.89	65.70	76.05	89.34	0.00	0.00
400.	44.84	46.50	48.32	50.29	52.40	63.72	73.71	87.44	104.67	0.00
410.	45.81	47.28	48.86	50.56	52.38	62.40	71.81	85.69	103.23	0.00
420.	46.88	48.21	49.62	51.12	52.71	61.61	70.36	84.13	101.91	0.00
430.	48.05	49.26	50.53	51.88	53.30	61.26	69.35	82.84	100.71	0.00
440.	49.29	50.40	51.57	52.79	54.07	61.25	68.73	81.70	99.64	0.00
450.	50.58	51.62	52.70	53.82	54.99	61.51	68.42	80.84	98.69	0.00
460.	51.93	52.90	53.90	54.94	56.01	61.98	68.38	80.21	97.86	113.60
470.	53.33	54.23	55.17	56.13	57.13	62.62	68.56	79.80	97.16	112.87
480.	54.76	55.61	56.49	57.39	58.32	63.40	68.92	79.57	96.59	112.22
490.	56.22	57.03	57.86	58.71	59.58	64.30	69.44	79.53	96.14	111.67
500.	57.72	58.48	59.26	60.06	60.88	65.29	70.09	79.64	95.81	111.20

TABLE6. VISCOSITY AND THERMAL CONDUCTIVITY
COEFFICIENTS OF SATURATED LIQUID ETHANE.

TEMPERATURE KELVIN	DENSITY MOLES/L	VISCOSITY MICRO-G/(CM*S)	THERMAL CONDUCTIVITY MILLI-W/(M*K)
200.0	17.456	1389.9	172.0
205.0	17.235	1313.1	161.6
210.0	17.009	1241.4	152.8
215.0	16.778	1174.3	145.3
220.0	16.541	1111.2	138.7
225.0	16.296	1051.5	132.9
230.0	16.044	995.1	127.7
235.0	15.784	941.4	123.0
240.0	15.514	890.1	118.7
245.0	15.233	841.0	114.7
250.0	14.939	793.8	110.9
255.0	14.631	748.1	107.3
260.0	14.306	703.8	103.7
265.0	13.961	660.6	100.2
270.0	13.592	618.2	96.8
275.0	13.193	576.3	93.3
280.0	12.755	534.4	89.8
285.0	12.265	492.1	86.4
290.0	11.702	448.3	83.2
295.0	11.021	401.5	80.5
300.0	10.105	347.3	78.8
305.0	8.073	254.7	85.1

6. Acknowledgments

H. Hanley was supported by the Office of Standard Reference Data. K. Gubbins and S. Murad were supported in part by the American Gas Association.

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