A Correlation of the Viscosity and Thermal Conductivity Data of Gaseous and Liquid Propane

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Data for the viscosity and thermal conductivity of gaseous and liquid propane have been evaluated and represented by empirical functions developed in previous work. Tables of values are presented for the range 140-500 K for pressures to 50 MPa (≈500 atm). The viscosities are estimated to have uncertainties of about ±5%, with corresponding uncertainties of the thermal conductivities of about ±8%. It is stressed that the data base should be improved. As in our work with other fluids, the anomalous contribution to the thermal conductivity in the vicinity of the critical point is included.

Key words: Critical point enhancement; correlated data; data evaluation; propane; thermal conductivity; viscosity.

Contents

Nomenclature

T	temperature, K
p	pressure, MPa
ρ	mass density
K_T	compressibility
η	viscosity, $\mu g/(cm \cdot s)$ [1]
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, $mW/(m \cdot K)$
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

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[1] To convert from g/(cm • s) to Pa • s, multiply by 10^{-1}.

Θ	viscosity and thermal conductivity equation variable
*	reduced variable superscript
c	critical point variable subscript
$x_o, B, E_1, E_2, \delta, \gamma$	scaling parameters for the compressibility in the critical region
R	length parameter in the critical point equation
μ	chemical potential

1. Introduction

This work is part of a series of papers, published in this Journal, on the transport properties of pure fluids. We have discussed argon (with krypton and xenon), oxygen and nitrogen [1],[2] methane [2] and ethane [3]. Propane is now included and tables of the viscosity (η) and the thermal conductivity (λ) are presented.

The evaluation and correlation of the experimental data for propane followed closely the procedure described in reference [3] for ethane. The data base for these fluids is similar; several authors report measurements for both fluids. However, as for ethane, the data are not always satisfactory by present day measurement standards. Nevertheless, we thought it worthwhile to present tables for both the viscosity and thermal conductivity over a wide range of experimental conditions with the reservation that the tables will probably have to be revised when more accurate data become available, particularly for the thermal conductivity. Other correlations are in the literature [4], but they are most often restricted to one of the coefficients and/or cover a limited experimental range. There are also quite large discrepancies between corresponding tabulated values from the various correlated sets.

Since we repeated essentially the procedure of reference [3], the discussion in this paper is abbreviated. Further, we refer to reference [1] for details on our criteria for the critical evaluation of transport data.

2. Correlating Equations

The correlation for propane was based on the behavior of the transport properties with respect to temperature (T) and density (ρ) according to the equations

$$\eta(\rho, T) = \eta_o(T) + \eta_1(T)\rho + \Delta\eta'(\rho, T) + \Delta\eta_c(\rho, T) \quad (1)$$

$$\lambda(\rho, T) = \lambda_o(T) + \lambda_1(T)\rho + \Delta\lambda'(\rho, T) + \Delta\lambda_c(\rho, T) \quad (2)$$

for the viscosity and thermal conductivity, respectively. In these equations, $\eta_o(T)$ and $\lambda_o(T)$ 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

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

[2] Figures in brackets indicate the literature references.

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 propane pair potential function and k is Boltzmann's constant.

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

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

and

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

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, $j_1 \ldots j_7$, $k_1 \ldots k_7$, are 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 (although $\Delta\eta_c$ will be set equal to zero in this work).

2.1. The Equation of State

We have argued that the transport properties should be correlated in terms of temperature and density. A thermodynamic equation of state is thus an integral part of the correlation scheme. The equation of state used for propane was that proposed by Goodwin and reported in reference [5].

3. Data

The following references which reported experimental data were examined: viscosity, references [6-35]; and thermal conductivity, references [17, 36-48]. The literature data were evaluated as far as possible by the same criteria discussed in reference [1].

As indicated by the form of equations (1) and (2), we find it convenient to consider the dilute gas, the dense gas and liquid, and the critical region separately.

3.1. The Dilute Gas

Following our usual procedure, the dilute gas viscosity and thermal conductivity data were fitted by least squares to the expansions

$$\eta_o = GV(1)T^{-1} + GV(2)T^{-2/3} + GV(3)T^{-1/3} + GV(4) + GV(5)T^{1/3} + GV(6)T^{2/3} + GV(7)T + GV(8)T^{4/3} + GV(9)T^{5/3}, \quad (7)$$

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

respectively. $GV(1)$ . . . $GV(9)$ and $GT(1)$ . . . $GT(9)$ are empirical coefficients. References for the data selected for the fits are shown in table 1 together with the temperature range and our estimate of the accuracy. Coefficients for equations (7) and (8) are given in table 2.

The data base for the dilute gas viscosity is satisfactory over a limited temperature range: the modern data from references [18] and [19] cover 296-478 K and we have extended this range slightly by including adjusted data from references [14] and [15]. As discussed in reference [1], there are strong arguments that the data from these references are subject to a small systematic error, but that this error can be accounted for. See, also figure 1 of reference [49].

The fit was weighted slightly to the data of references [18] and [19]. Theoretical points at 150 K and at 1200 K were included in the fit. These theoretical points were obtained from kinetic theory with the m-6-8 potential function (see below) and were considered only to ensure that the function (7) is well behaved outside the data range.

Figure 1 shows the deviation plot, where percent deviation, here and in the other figures, is given by

$$\frac{\eta(\text{exp}) - \eta(\text{calc})}{\eta(\text{exp})} \cdot 100. \quad (9)$$

One observes the fit is to within ±0.5%.

In contrast, the dilute gas thermal conductivity data situation is not very good. The data are often not internally consistent and different data sets differ by up to 8% at corresponding temperatures. We assessed the data to ±6% accuracy and fitted all the data listed in table 1 giving equal weight to all points. The deviation curve is shown in figure 2 and is self-explanatory.[3]

Fit of the m-6-8 potential to the viscosity data.

The utility of statistical mechanical expressions, with a realistic intermolecular potential function, to represent the properties of a dilute gas has been emphasized by us and by other authors. We have had considerable success with the m-6-8 potential [1, 49].

[3] Reference [36] reports experimental dilute gas thermal conductivities from 300 to 1000 K represented by an empirical function. We included the values at 1000 K to ensure the function was well behaved at this temperature. Our correlation agrees to within ±2% of this data set, overall.

Table 1. Selected data for propane

References	temperature range K	pressure limit MPa	estimated accuracy %
VISCOSITY			
	Dilute gas		
[14], [15]	291 - 548	--	1.25[a]
[18], [19]	296 - 478	--	0.3
[20]	293 - 371	--	1.5
	Dense gas and liquid		
[9]	173 - 273	34	4
[12]	324 - 408	54	5
[29]	89 - 511	136	5
[30]	278 - 478	34	5
[31]	278 - 378	54	3
THERMAL CONDUCTIVITY			
	Dilute gas		
[17], [38-40], [42-48]	233 - 505	--	6
	Dense gas and liquid		
[38]	323 - 413	28	6
[39]	212 - 412	50	7
[40]	278 - 478	34	5
[41]	93 - 223	sat. liquid	6

[a] These data were adjusted, see text.

Table 2. Dilute Gas Parameters for Equations (7) and (8). Units - Temperature in K, Viscosity in μg/(cm·s) and Thermal Conductivity in mW/(m·K).

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GV(1)=-.1132608333E+07
GV(2)= .8465572858E+06
GV(3)=-.2314345388E+06
GV(4)= .2089338580E+05
GV(5)= .2693257510E+04
GV(6)=-.8709423636E+03
GV(7)= .9216623121E+02
GV(8)=-.4593654804E+01
GV(9)= .9088758027E-01

GT(1)=-.1089381103E+07
GT(2)= .8343297829E+06
GT(3)=-.2270902736E+06
GT(4)= .1667866368E+05
GT(5)= .4347320565E+04
GT(6)=-.1177734671E+04
GT(7)= .1215425833E+03
GT(8)=-.6040596921E+01
GT(9)= .1207373681E+00
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The m-6-8 potential is given by the expression

$$\frac{\Phi(r^*)}{\epsilon}=\frac{1}{m-6}[6+2\gamma'](d/r^*)^m-\frac{1}{m-6}$$
$$[m-\gamma'(m-8)](d/r^*)^6-\gamma'(d/r^*)^8. \qquad (10)$$

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 $\Phi(\sigma)=0$. γ' is a parameter which represents inverse-eighth power attraction in the potential.

The dilute gas viscosity data were used to obtain m-6-8 parameters via the standard kinetic theory expression for η_o. Values of the m-6-8 parameters are given in table 3. The potential is used specifically in the study to extend the effective temperature range of the dilute gas data, and to calculate the thermal conductivity in the vicinity of the critical point (section 3.3).

3.2. The Dense Gas and Liquid

Having values for $\eta_o(T)$ and setting $\Delta\eta_c(\rho,T)$ 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).

References for the data selected are given in table 1. Qualitatively, the data seem very reasonable and no serious discrepancies exist between the selected data sets. Equal weight was given to all data, and an accuracy of ±5% was assigned. The experimental range covered is fairly extensive except that data for the moderately dense gas (densi-

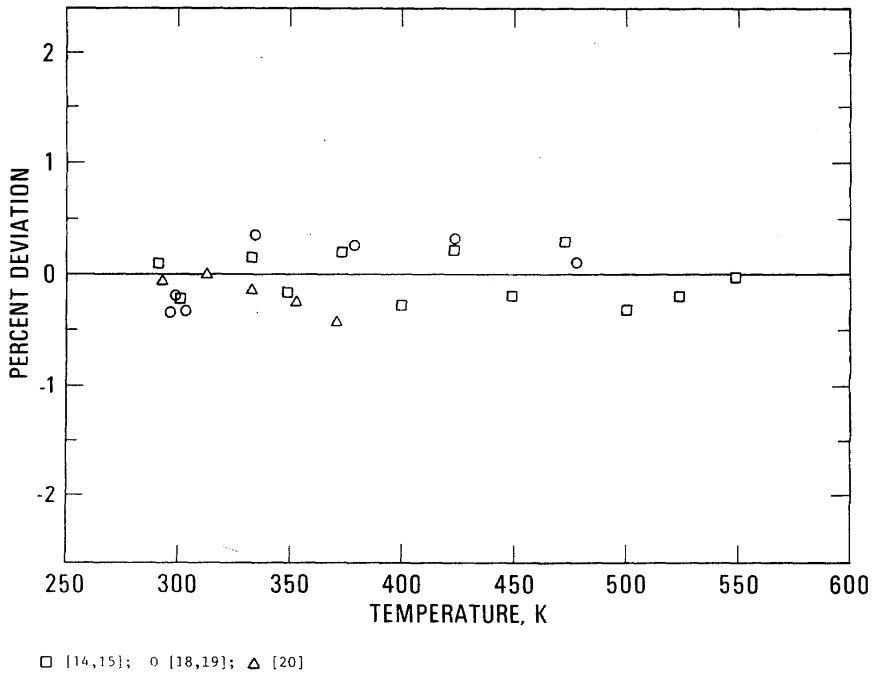

FIGURE 1. Dilute gas viscosity: deviations between experimental data and values from equation (7).

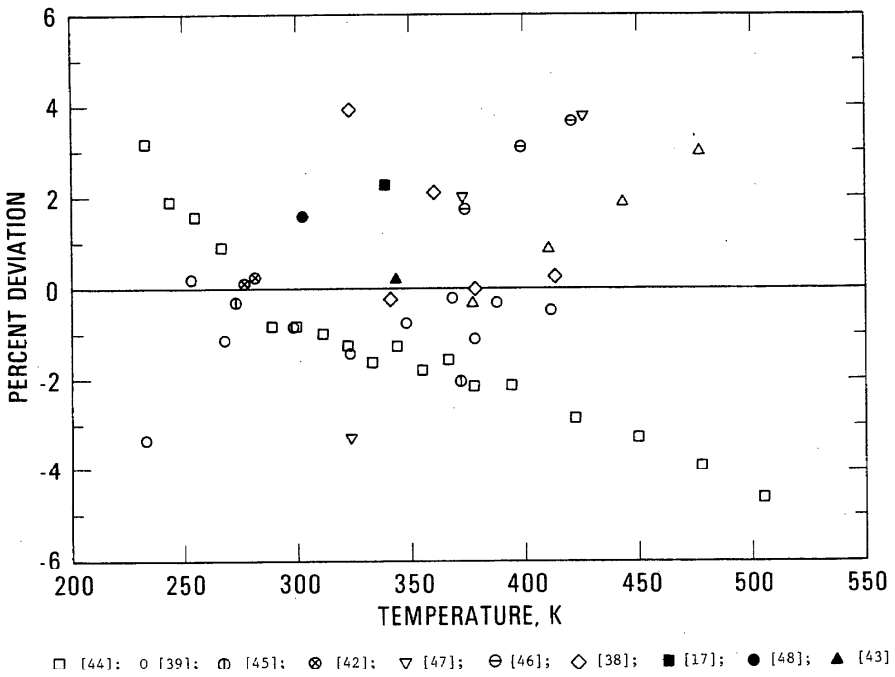

FIGURE 2. Dilute gas thermal conductivity: deviations between experimental data and values from equation (8).

Table 3. Critical point constants, parameters for the m-6-8 potential [equation (10)], and parameters for the conductivity equation (11).

Critical point constants[b]	
T_c	369.82 K
ρ_c	0.221 g/cm^3 (5.011 mol/L)
P_c	4.3569 MPa (43.037 atm)
M	44.10
Parameters for equation (10)	
ε/k	358.9 K
σ	4.700×10^{-10} m
r_m	5.238×10^{-10} m
γ'	3.0
m	11
Parameters for equations (14) and (16)	
E_1	1.83
E_2	0.287
x_o	0.137
β	0.355
γ	1.190
δ	4.352

[b] These values differ slightly from the values reported in reference [5]. They were selected to be consistent with equations (14) and (16).

Table 4. Parameters for Equations (3)-(5). Units - Temperature in K, Viscosity in μg/(cm•s) and Thermal Conductivity in mW/(m•K).

VISCOSITY

EQUATION 3 A=0.0

B=0.0

C=1.12

F=358.9

EQUATION 4 F=1.0

J1=-.1496346267E+02

J2= .2179858583E+02

J3=-.2566988314E+05

J4= .1527903946E+04

J5=-.2112678461E+00

J6= .2127695241E+03

J7= .5515987919E+05

THERMAL CONDUCTIVITY

EQUATION 3 A=-1.149813131

B= .788531221

C=1.12

F=358.9

EQUATION 5 D=1.0

K1=-.1092449464E+02

K2= .1480622080E+02

K3=-.1874097856E+05

K4= .1269709514E+04

K5=-.9598486895E-01

K6= .1389024749E+03

K7= .2554581504E+05

ties less than ⅔ ρ_c, where ρ_c is the critical density) are relatively sparse and scattered. Because of their scarcity in this region we found that the data were best fitted if the term $\eta_1(T)$ was set equal to zero.

Values of the coefficients $A(=0)$, $B(=0)$, C, F, and $J_1 \ldots J_7$ are given in table 4.

Representative deviation curves are shown as figures 3-5. It is seen that these data points are fitted to within about ±2%, which is inside our error estimate for the data themselves.

Figure 6 gives the plot of the excess thermal conductivity coefficient, $\Delta\lambda$, versus density for some of the data noted in table 1. The excess is defined by $\Delta\lambda(\rho, T) = \lambda(\rho, T) - \lambda_o(T)$, i.e., $\lambda(\rho, T)$, the experimental value, less the corresponding value of the dilute gas.

For the temperature ranges reported (although not in general) a plot of $\Delta\lambda$ versus ρ should be essentially a smooth curve, independent of temperature. This observation is based on the experimental behavior of simple fluids (N_2, O_2, CH_4, etc.) [1]. From the plot, therefore, one obtains an idea of the internal consistency of the data from a particular author, and the differences between authors which, in this case, are quite large, even ignoring the scatter of the data around the critical density.

The scatter around the critical density represents points close to the critical temperature. This scatter is of interest since it demonstrates qualitatively the anomalous increase in the thermal conductivity coefficient, $\Delta\lambda_c$, in this region. Propane was one of the first fluids for which this phenomenon was noticed. However, here it is clear that the anom-

aly is only crudely represented and these data points were not included in the fit.

As for the viscosity, the contribution $\lambda_o(T)$ was extracted from the selected data which were then fitted to the terms $[\lambda_1(T)\rho+\Delta\lambda'(\rho,T)]$ of equation (2). Slight weight was given to the data of reference [40]. The coefficients for the fit are given in table 4. Sample deviation plots are given in figures 7-9 and one sees that the data are fitted to within the experimental accuracy.

3.3. The Critical Region

Following the precedent set in our previous work [1-3], we feel confident in neglecting the propane thermal conductivity data in the vicinity of the critical point and estimating $\Delta\lambda_c(\rho,T)$ by calculation. This approach has been reinforced recently since we have shown that the calculation procedure can represent the anomaly $\Delta\lambda_c$ for methane to within about $\pm 15\%$ extremely close to the critical point (to $T-T_c=10^{-3}$ K at the critical isochore [50]). The procedure is discussed in Section 3.2 of reference [1] and in reference [51].

According to reference [51],

$$\Delta\lambda_c(\rho,T)=\left(\frac{M}{\rho NkT}\right)^{1/2}\frac{kT^2}{6\pi\eta R}\left(\frac{\partial P}{\partial T}\right)_\rho^2 (K_T)^{1/2}\exp(-18.66\,\tilde{\Delta}T^2)\exp(-4.25\,\tilde{\Delta}\rho^4), \quad (11)$$

where

$$\tilde{\Delta}T=|T-T_c|/T_c;\ \tilde{\Delta}\rho=|\rho-\rho_c|/\rho_c. \quad (12)$$

In equation (11) 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:

$$R=r_m^{5/2}\left(\frac{N\rho}{T^*}\right)^{1/2}\left(\frac{2\pi}{3}\right)\left[\frac{m-\gamma'(m-8)}{m-6}+\frac{\gamma'}{3}\right]^{1/2}, \quad (13)$$

where $T^*=T/(\epsilon/k)$, m, γ', r_m and ϵ/k are the m-6-8 parameters of equation (10).

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 [5]. 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 correctly 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:

$$\rho^2K_T=\frac{\rho_c}{P_c}|\tilde{\Delta}\rho|^{(1-\delta)}\left[h(x)-\frac{x}{\beta}h'(x)\right]^{-1}, \quad (14)$$

where $h'(x)\equiv dh(x)/dx$. The derivation of equation (14) 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

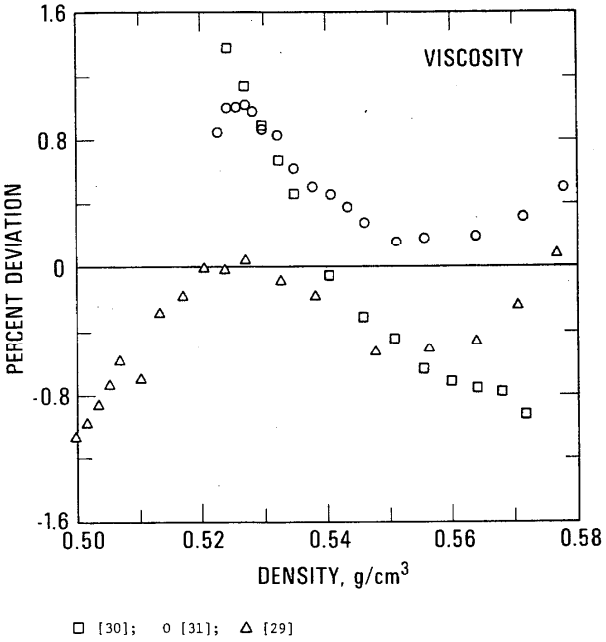

FIGURE 3. Deviation plot for liquid viscosities at approximately 280 K.

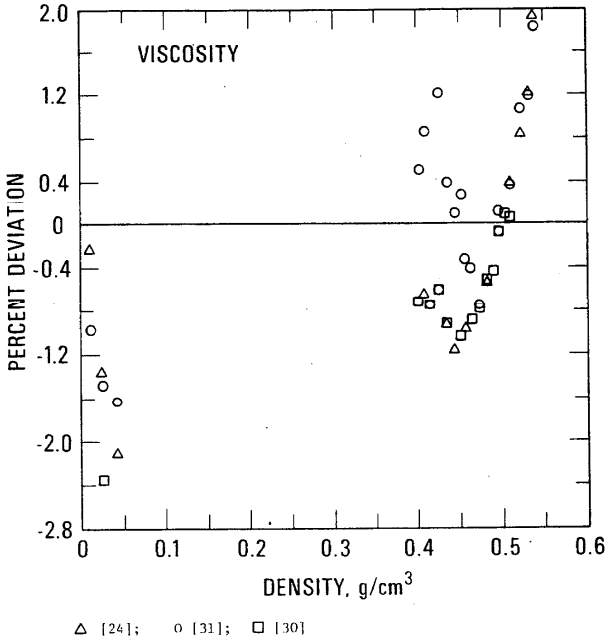

FIGURE 4. Deviation plot for liquid viscosities at approximately 344 K.

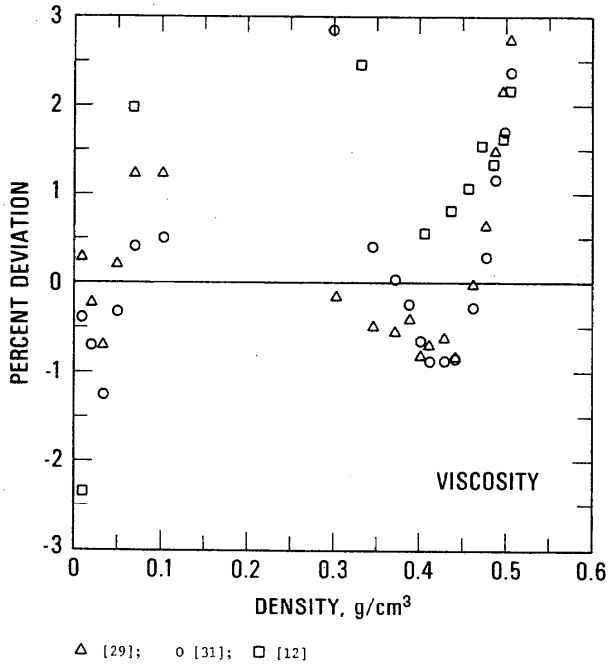

FIGURE 5. Deviation for gaseous propane viscosities at approximately 380 K.

curve varies asymptotically as $|\tilde{\Delta}\rho| \propto |\tilde{\Delta}T|^{\beta}$; the chemical potential $\mu(\rho, T)$ along the critical isotherm varies as $\mu(\rho, T) - \mu(\rho_c, T_c) \propto |\tilde{\Delta}\rho|^{\delta}$; 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:

$$x = \tilde{\Delta}T / |\tilde{\Delta}\rho|^{1/\beta}, \tag{15}$$

and $h(x)$ is a function:

$$h(x) = E_1\left(\frac{x+x_o}{x_o}\right)\left[1+E_2\left(\frac{x+x_o}{x_o}\right)^{2\beta}\right]^{(\gamma-1)/2\beta}. \tag{16}$$

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_o, E_1 and E_2. Values of the constants and exponents are listed in table 3.

To illustrate the influence of the critical point, we have plotted in figure 10 the calculated excess thermal conductivity coefficient $\Delta\lambda$ versus density at three temperatures; 369.95, 371.0, and 380.0 K. The conductivity in the absence of the anomaly is that from equation (2) $[\Delta\lambda_c = 0]$, while $\Delta\lambda_c$ was obtained as described from equation (11).

Alternative calculation of $\Delta\lambda_c$: alternative for R

It should be remarked that an alternative and more systematic procedure to calculate the length parameter R has been introduced by Sengers [52]. We will not discuss this further here, however, beyond pointing out that the Sengers procedure has been compared with that used here [50]. Numerical differences in R at corresponding temperatures and densities turn out to be small (about 10% or less).

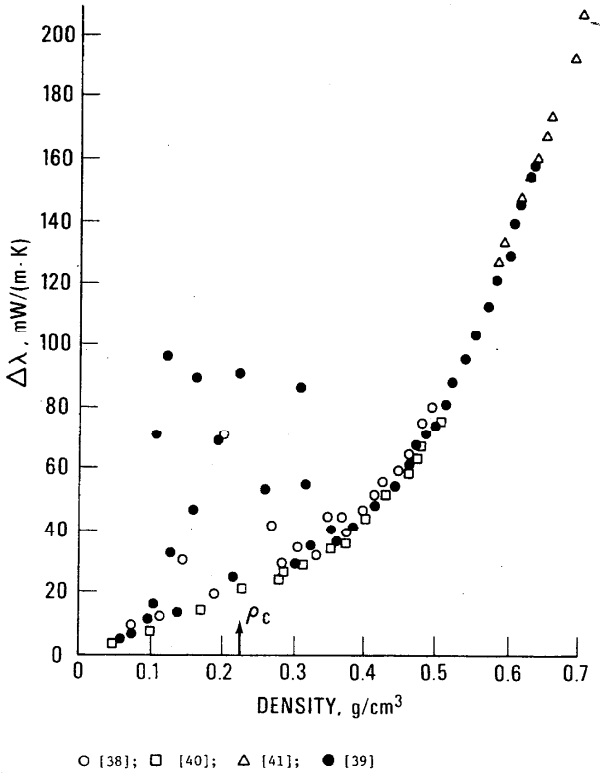

FIGURE 6. Plot of the excess thermal conductivity versus density.

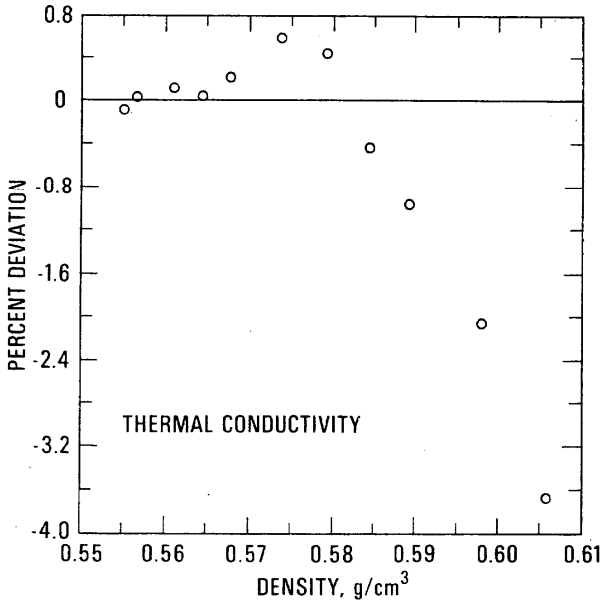

FIGURE 7. Deviation plot for the thermal conductivity at 253 K, data from reference [39].

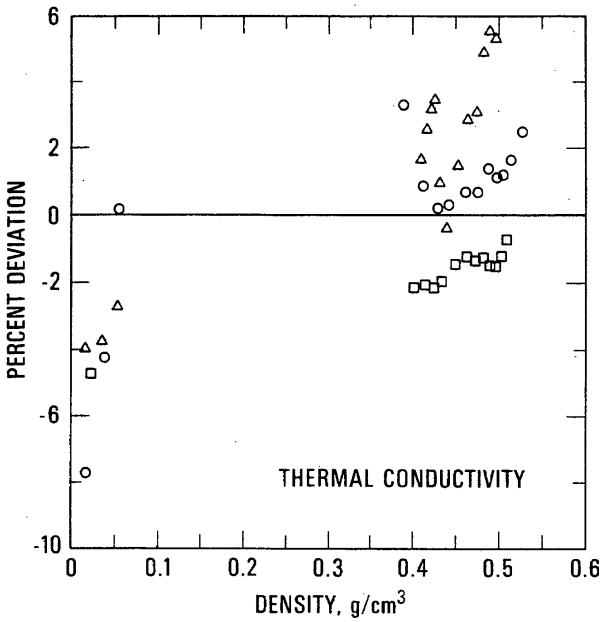

FIGURE 8. Deviation plot for the thermal conductivity at approximately 345 K.

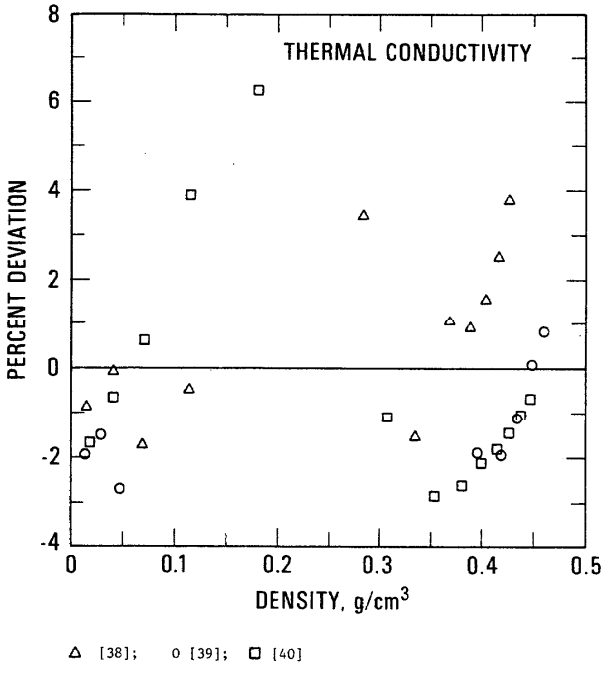

FIGURE 9. Deviation plot for the thermal conductivity at approximately 410 K.

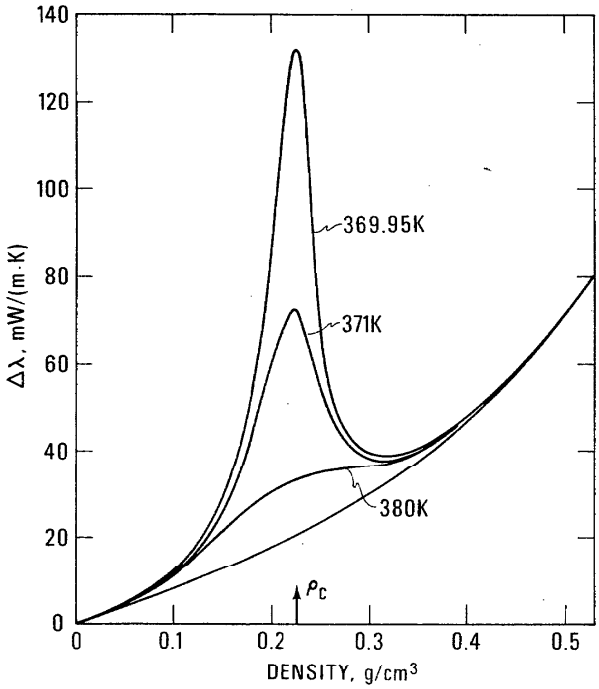

FIGURE 10. The excess thermal conductivity of propane showing the enhancement at three temperatures.

Alternative calculation of $\Delta\lambda_c$: from corresponding states

If two-parameter corresponding states is obeyed, one can write $\Delta\lambda_c(\rho, T)$ for a given fluid in terms of equivalent values from a reference fluid, superscript o:

$$\Delta\lambda_c(\rho, T) = \Delta\lambda^o_c(\rho', T')\left(\frac{M^o}{M}\right)^{1/2}\left(\frac{\rho_c}{\rho^o_c}\right)^{2/3}\left(\frac{T_c}{T^o_c}\right)^{1/2}, \quad (17)$$

where

$$\rho' = \left(\frac{\rho}{\rho_c}\right)\rho^o_c; \quad T' = \left(\frac{T}{T_c}\right)T^o_c. \quad (18)$$

The concept of two-parameter corresponding states is sensible in this context since it implies that the critical behavior of fluids is not too dependent on the nature of the fluid. Figure 11 shows the excess thermal conductivity of propane (solid line) at 369.9 K plotted versus the reduced density ρ/ρ_c. The points were obtained from equation (17) with methane as the reference substance. The agreement is ±15% or better, which is excellent in this context.

Viscosity

It is known that the viscosity also displays anomalous behavior in the critical region, but that this anomaly is much less pronounced than its counterpart for the thermal conductivity. As in our previous work, this is not considered in the correlation.

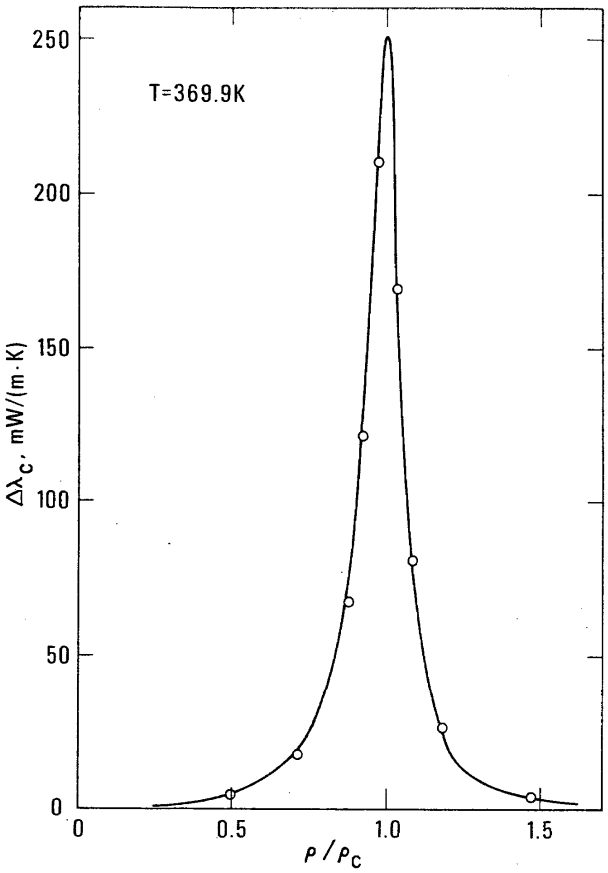

FIGURE 11. Plot of the critical point enhancement in the thermal conductivity calculated at 369.9 K from equation (11) (line). Also shown (points) are equivalent values obtained via the corresponding states equation (17).

4. Tables of Values

The viscosity and thermal conductivity coefficients of propane have been calculated for 140-500 K for pressures up to 50 MPa (≈500 atm). Tabular values are presented as tables 5 and 6. We ensured that an entry in the table would not require an extrapolation much beyond the range of data. Gaps in the tables indicate that the *P-T* points correspond to densities exceeding 0.71 g/cm^3, the upper density limit for the data for temperatures less than 300 K, or 0.26 g/cm^3 for the higher temperatures. For convenience saturated liquid values have been listed separately as table 7 and dilute gas values as table 8. (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

The uncertainty of the tabulated values can be judged from our estimate of accuracy of the input data, and the deviation plots, figures 1-5, 6-8. We attempted to evaluate the data using the criteria of reference [1] but this was not always possible: lack of experimental details was the principal drawback. In short, an estimate of uncertainty of the tables has to be somewhat subjective in that it is influenced by our experience of evaluating similar data for fluids which have a better data base. Overall, we judge the viscosity coefficient to have an uncertainty of ±5%, and the thermal conductivity to have an uncertainty of ±8%. In the critical region, this latter estimate should be increased to ±15%.

5. Conclusion

As in our previous work, a general empirical equation has been used to represent the viscosity and thermal conductivity coefficients of propane from the dilute gas to the dense liquid. Tables of calculated values are presented.

As pointed out in the Introduction, the tables have to be considered somewhat tentative since the data base from which they were constructed could be improved. To repeat the remark made with respect to ethane [3], it would be helpful if the more recent experimental techniques devised to measure the transport coefficients could be applied to propane. It would be especially useful to have reliable viscosity data for the dilute gas outside the range reported here. Viscosity data for the moderately dense gas are also scarce.

6. Acknowledgments

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Table 5. Viscosity of Propane, μg/(cm•s).

T, K	P, MPa .1	.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0
140.	8421.5	8457.0	8501.5	8546.0	8590.6	8635.1	8679.7	8724.4	8769.1	8858.6
150.	6577.4	6604.7	6638.7	6672.8	6706.9	6741.1	6775.2	6809.4	6843.6	6912.0
160.	5320.5	5342.4	5369.7	5397.0	5424.3	5451.6	5478.9	5506.2	5533.5	5588.2
170.	4410.9	4427.0	4449.6	4472.3	4494.9	4517.5	4540.1	4562.7	4585.3	4640.5
180.	3745.0	3760.4	3779.7	3799.0	3818.3	3837.5	3856.7	3876.0	3895.2	3933.6
190.	3224.1	3237.6	3254.4	3271.2	3288.0	3304.8	3321.5	3338.3	3355.0	3388.4
200.	2810.1	2822.1	2837.1	2852.1	2867.0	2881.9	2896.8	2911.6	2926.5	2956.1
210.	2473.3	2484.2	2497.7	2511.3	2524.8	2538.3	2551.7	2565.1	2578.5	2605.3
220.	2193.6	2203.6	2216.1	2228.6	2241.0	2253.4	2265.7	2278.0	2290.3	2314.8
230.	1957.3	1966.7	1978.3	1989.9	2001.5	2013.0	2024.5	2036.0	2047.4	2070.2
240.	66.6	1763.3	1774.4	1785.3	1796.3	1807.2	1818.0	1828.8	1839.6	1861.0
250.	69.3	1586.3	1596.9	1607.5	1618.0	1628.4	1638.8	1649.1	1659.4	1679.8
260.	71.9	1430.3	1440.6	1450.8	1461.0	1471.1	1481.2	1491.2	1501.1	1520.8
270.	74.6	1290.8	1301.0	1311.1	1321.2	1331.1	1341.0	1350.8	1360.5	1379.8
280.	77.2	78.9	1174.9	1185.1	1195.1	1205.0	1214.9	1224.6	1234.3	1253.3
290.	79.9	81.5	1059.4	1069.8	1080.0	1090.1	1100.1	1109.9	1119.6	1138.8

T, K	P, MPa 6.0	7.0	8.0	9.0	10.0	15.0	20.0	30.0	40.0	50.0
140.	8948.3	9038.2	9128.2	9218.4	9308.8	9763.5	10222.4	11152.9	12099.7	13062.1
150.	6980.6	7049.2	7117.9	7186.7	7255.6	7601.2	7948.8	8650.1	9359.3	10076.3
160.	5642.9	5697.6	5752.3	5807.1	5861.9	6136.3	6411.5	6964.0	7519.5	8078.0
170.	4685.6	4730.8	4776.0	4821.1	4866.2	5091.8	5317.1	5767.7	6218.1	6668.8
180.	3972.0	4010.3	4048.6	4086.8	4125.0	4315.6	4505.4	4883.1	5258.7	5632.7
190.	3421.7	3455.0	3488.2	3521.4	3554.5	3719.2	3882.8	4206.7	4527.1	4844.6
200.	2985.7	3015.1	3044.5	3073.8	3103.1	3248.2	3391.8	3675.0	3953.5	4228.2
210.	2631.9	2658.4	2684.9	2711.2	2737.5	2867.6	2995.8	3247.3	3493.3	3734.9
220.	2339.2	2363.4	2387.6	2411.6	2435.6	2553.8	2669.9	2896.5	3116.9	3332.1
230.	2092.8	2115.3	2137.6	2159.9	2182.0	2290.9	2397.4	2604.0	2803.8	2997.9
240.	1882.3	1903.4	1924.4	1945.2	1965.8	2067.4	2166.1	2356.6	2539.6	2716.5
250.	1700.0	1720.1	1739.9	1759.7	1779.2	1874.9	1967.4	2144.8	2314.1	2476.9
260.	1540.3	1559.6	1578.6	1597.5	1616.2	1707.3	1794.9	1961.6	2119.4	2270.3
270.	1398.8	1417.5	1436.0	1454.3	1472.4	1560.0	1643.6	1801.4	1949.8	2090.4
280.	1272.1	1290.5	1308.7	1326.6	1344.2	1429.2	1509.7	1660.4	1800.1	1931.4
290.	1157.5	1175.9	1193.9	1211.6	1229.1	1312.4	1390.5	1535.3	1669.7	1793.4

Table 5. Viscosity of Propane, μg/(cm. s)--Continued

T, K	P, MPa .1	.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0
300.	82.6	84.1	952.0	962.8	973.5	984.0	994.3	1004.4	1014.4	1033.9
320.	87.9	89.3	91.5	94.6	777.2	789.5	801.4	813.0	824.2	845.9
340.	93.2	94.5	96.4	99.1	102.8	599.9	617.2	633.2	648.1	675.5
360.	98.5	99.6	101.4	103.7	106.7	110.8	117.0	130.0	452.7	503.9
380.	103.8	104.8	106.3	108.4	110.9	114.1	118.4	124.2	133.3	210.8
400.	109.0	109.9	111.3	113.1	115.3	118.0	121.3	125.5	130.9	148.4
420.	114.1	114.9	116.2	117.8	119.8	122.1	124.9	128.2	132.3	143.4
440.	119.2	119.9	121.1	122.6	124.3	126.3	128.8	131.6	134.8	143.2
460.	124.2	124.9	126.0	127.3	128.8	130.7	132.8	135.2	138.0	144.7
480.	129.2	129.8	130.8	132.0	133.4	135.0	136.9	139.0	141.4	147.2
500.	134.1	134.6	135.5	136.6	137.9	139.4	141.1	143.0	145.1	150.1

T, K	P_r, MPa 6.0	7.0	8.0	9.0	10.0	15.0	20.0	30.0	40.0	50.0
300.	1052.9	1071.5								
320.	866.5	886.4	905.5	924.0	941.9	1024.7				
340.	700.5	723.6	745.2	765.6	785.1	871.7	946.6	1076.1		
360.	541.5	572.7	599.9	624.4	647.0	741.2	818.1	945.8	1053.9	
380.	359.8	419.8	461.1	494.1	522.3	629.0	709.2	836.4	941.0	1032.6
400.	187.4	256.9	322.5	371.0	408.5	532.5	616.8	744.2	845.8	933.5
420.	160.8	188.7	227.5	270.5	311.2	450.4	538.7	666.2	765.2	849.4
440.	154.8	170.9	192.6	219.3	248.9	382.5	473.2	600.3	696.7	777.7
460.	153.6	165.0	179.4	197.1	217.5	329.4	418.9	544.6	638.3	716.3
480.	154.3	163.2	174.0	186.8	201.7	291.1	374.8	497.5	588.5	663.6
500.	156.1	163.4	172.0	182.0	193.5	265.2	339.9	457.8	545.8	618.2

Table 6. Thermal Conductivity of Propane, mW/(m·K).

T, K	P, MPa .1	.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0
140.	198.21	198.64	199.18	199.72	200.25	200.79	201.33	201.86	202.39	203.46
150.	190.98	191.40	191.91	192.43	192.94	193.45	193.96	194.47	194.98	196.00
160.	183.02	183.41	183.90	184.40	184.89	185.38	185.87	186.36	186.85	187.82
170.	174.73	175.11	175.59	176.06	176.54	177.01	177.48	177.95	178.41	179.35
180.	166.43	166.79	167.25	167.71	168.17	168.62	169.07	169.53	169.98	170.88
190.	158.28	158.63	159.08	159.52	159.97	160.41	160.85	161.29	161.72	162.59
200.	150.40	150.75	151.19	151.62	152.05	152.48	152.91	153.34	153.76	154.61
210.	142.87	143.21	143.64	144.07	144.49	144.91	145.33	145.75	146.17	146.99
220.	135.71	136.05	136.47	136.89	137.31	137.72	138.14	138.55	138.96	139.78
230.	128.92	129.26	129.68	130.10	130.51	130.93	131.34	131.75	132.16	132.97
240.	12.52	122.84	123.26	123.68	124.10	124.51	124.93	125.34	125.74	126.55
250.	13.40	116.76	117.19	117.62	118.04	118.46	118.88	119.29	119.70	120.52
260.	14.34	111.01	111.45	111.89	112.32	112.75	113.17	113.59	114.01	114.84
270.	15.31	105.53	105.99	106.44	106.89	107.33	107.77	108.21	108.64	109.48
280.	16.33	17.29	100.77	101.25	101.72	102.18	102.64	103.09	103.54	104.42
290.	17.37	18.29	95.75	96.26	96.76	97.25	97.74	98.22	98.69	99.61

T, K	P, MPa 6.0	7.0	8.0	9.0	10.0	15.0	20.0	30.0	40.0	50.0
140.	204.52	205.58	206.64	207.70	208.75	213.97	219.12	229.25	239.16	248.87
150.	197.01	198.02	199.03	200.03	201.03	205.99	210.87	220.42	229.72	238.79
160.	188.79	189.75	190.71	191.67	192.62	197.33	201.96	210.99	219.74	228.24
170.	180.27	181.20	182.12	183.03	183.94	188.44	192.85	201.40	209.66	217.65
180.	171.77	172.66	173.54	174.42	175.30	179.60	183.81	191.95	199.77	207.31
190.	163.46	164.31	165.17	166.02	166.88	171.01	175.04	182.81	190.24	197.38
200.	155.45	156.28	157.11	157.93	158.75	162.76	166.64	174.10	181.19	187.96
210.	147.82	148.63	149.44	150.24	151.04	154.93	158.69	165.87	172.66	179.12
220.	140.58	141.38	142.18	142.96	143.74	147.54	151.20	158.14	164.67	170.85
230.	133.76	134.56	135.34	136.11	136.88	140.61	144.19	150.93	157.23	163.17
240.	127.35	128.14	128.91	129.68	130.44	134.13	137.64	144.22	150.33	156.06
250.	121.32	122.11	122.89	123.65	124.41	128.07	131.54	137.99	143.94	149.48
260.	115.65	116.44	117.23	118.00	118.77	122.42	125.86	132.22	138.03	143.41
270.	110.31	111.12	111.92	112.71	113.48	117.16	120.59	126.88	132.57	137.82
280.	105.27	106.11	106.93	107.73	108.52	112.25	115.69	121.94	127.54	132.67
290.	100.50	101.37	102.22	103.05	103.86	107.66	111.14	117.37	122.91	127.94

Table 6. Thermal Conductivity of Propane, mW/(m·K)--Continued

T, K	P, MPa .1	.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0
300.	18.44	19.32	90.85	91.41	91.95	92.49	93.01	93.53	94.03	95.01
320.	20.66	21.46	22.38	23.49	82.47	83.16	83.83	84.47	85.09	86.28
340.	22.96	23.69	24.52	25.44	26.66	73.40	74.40	75.33	76.20	77.80
360.	25.34	26.00	26.75	27.56	28.52	29.81	31.93	37.93	67.49	69.69
380.	27.79	28.39	29.07	29.78	30.59	31.56	32.84	34.70	37.81	58.65
400.	30.30	30.85	31.47	32.10	32.80	33.59	34.53	35.71	37.26	42.30
420.	32.87	33.37	33.94	34.51	35.12	35.78	36.54	37.41	38.45	41.25
440.	35.50	35.96	36.48	36.99	37.54	38.11	38.74	39.44	40.22	42.13
460.	38.18	38.61	39.09	39.56	40.04	40.56	41.10	41.68	42.32	43.76
480.	40.93	41.32	41.76	42.19	42.64	43.10	43.58	44.08	44.62	45.80
500.	43.73	44.09	44.50	44.90	45.31	45.72	46.16	46.61	47.08	48.08

T, K	P, MPa 6.0	7.0	8.0	9.0	10.0	15.0	20.0	30.0	40.0	50.0
300.	95.96	96.88								
320.	87.40	88.47	89.48	90.46	91.39	95.63				
340.	79.24	80.58	81.82	82.98	84.07	88.83	92.78	99.33		
360.	71.57	73.24	74.76	76.15	77.44	82.86	87.15	93.98	99.47	
380.	64.99	67.31	69.10	70.65	72.04	77.83	82.40	89.51	95.07	99.74
400.	50.78	58.41	63.04	65.79	67.74	74.01	78.62	85.87	91.48	96.13
420.	45.28	50.21	54.96	59.05	62.34	71.01	75.80	83.01	88.63	93.25
440.	44.61	47.62	50.93	54.20	57.27	67.97	73.56	80.88	86.45	91.02
460.	45.61	47.56	49.85	52.27	54.71	65.09	71.54	79.32	84.86	89.37
480.	47.15	48.68	50.37	52.19	54.08	63.13	69.87	78.18	83.77	88.23
500.	49.20	50.42	51.76	53.19	54.70	62.36	68.82	77.42	83.12	87.55

Table 7. Viscosity and Thermal Conductivity Coefficients of Saturated Liquid Propane.

TEMPERATURE KELVIN	DENSITY MOL/L	PRESSURE MPA	VISCOSITY μg/(cm•s)	THERMAL CONDUCTIVITY mW/(m•K)
140.0	15.375	.7697E-04	8412.6	198.1
150.0	15.144	.2741E-03	6570.6	190.9
160.0	14.910	.8220E-03	5315.1	182.9
170.0	14.676	.2139E-02	4414.5	174.6
180.0	14.438	.4945E-02	3741.3	166.3
190.0	14.198	.1035E-01	3221.1	158.2
200.0	13.954	.1993E-01	2807.7	150.3
210.0	13.707	.3574E-01	2471.5	142.8
220.0	13.454	.6031E-01	2192.6	135.7
230.0	13.196	.9661E-01	1957.2	128.9
240.0	12.930	.1480E+00	1755.5	122.5
250.0	12.657	.2182E+00	1580.3	116.5
260.0	12.373	.3112E+00	1426.3	110.8
270.0	12.078	.4312E+00	1289.4	105.5
280.0	11.769	.5828E+00	1166.4	100.4
290.0	11.442	.7706E+00	1054.6	95.5
300.0	11.095	.9997E+00	952.0	90.8
310.0	10.721	.1275E+01	856.7	86.3
320.0	10.312	.1603E+01	767.1	81.9
330.0	9.857	.1988E+01	681.4	77.5
340.0	9.333	.2436E+01	597.5	73.1
350.0	8.697	.2956E+01	512.3	69.4
360.0	7.831	.3555E+01	418.2	66.4

Table 8. Viscosity and Thermal Conductivity Coefficients of Dilute Gaseous Propane.

TEMPERATURE KELVIN	VISCOSITY μg/(cm·s)	THERMAL CONDUCTIVITY mW/(m·K)
140.0	39.9	6.2
160.0	45.5	6.8
180.0	50.6	7.5
200.0	55.7	8.7
220.0	60.8	10.1
240.0	66.1	11.8
260.0	71.4	13.7
280.0	76.8	15.8
300.0	82.2	18.0
320.0	87.6	20.2
340.0	92.9	22.6
360.0	98.3	25.0
380.0	103.6	27.5
400.0	108.8	30.0
420.0	113.9	32.6
440.0	119.0	35.3
460.0	124.1	38.0
480.0	129.0	40.7
500.0	133.9	43.6

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