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Viscosity and Thermal Conductivity Equations for Nitrogen, Oxygen, Argon, and Air

E. W. Lemmon[1,2] **and R. T Jacobsen**[3]

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New formulations for the viscosity and thermal conductivity for nitrogen, oxygen, argon, and air are given. Air is treated as a pseudo-pure fluid using an approach adopted from previous research on the equation of state for air. The equations are valid over all liquid and vapor states, and a simplified cross-over equation was used to model the behavior of the critical enhancement for thermal conductivity. The extrapolation behavior of the equations for nitrogen and argon well below their triple points was monitored so that both could be used as reference equations for extended corresponding states applications. The uncertainties of calculated values from the equations are generally within 2% for nitrogen and argon and within 5% for oxygen and air, except in the critical region where the uncertainties are higher. Comparisons with the available experimental data are given.

KEY WORDS: air; argon; nitrogen; oxygen; thermal conductivity; viscosity.

1. INTRODUCTION

The work presented here on the transport properties of air and its constituent fluids is the result of more than a decade of research on the properties of air at the University of Idaho and the National Institute of Standards and Technology (NIST). Publications resulting from this work include measurements on the PVT, isochoric heat capacity, and speed of sound of dry air (Howley et al. [1]; Magee [2]; Younglove and Frederick [3]), the viscosity of air (Diller et al. [4]), and the thermal conductivity of nitrogen

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[1] Physical and Chemical Properties Division, National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305, U.S.A.

[2] To whom correspondence should be addressed. E-mail: ericl@boulder.nist.gov

[3] Idaho National Engineering and Environmental Laboratory, P.O. Box 1625, Idaho Falls, Idaho 83415-2214, U.S.A.

(Perkins et al. [5, 6]; Roder et al. [7]), argon (Perkins et al. [5, 8]; Roder et al. [7, 9]), and air (Perkins and Cieszkiewicz [10]). From these measurements, equations of state representing the thermodynamic properties of air have been published (Jacobsen et al. [11, 12]; Panasiti et al. [13]; Lemmon et al. [14]), with the final paper reporting a mixture model for the nitrogen/argon/oxygen system in addition to an equation of state for air as a pseudo-pure fluid. Surface tension equations were given in Lemmon and Penoncello [15]. Preliminary equations for the transport properties were available in the REFPROP 7.0 database (Lemmon et al. [16]). The improved equations for the viscosity and thermal conductivity for nitrogen, argon, and oxygen along with air treated as a pseudo-pure fluid are reported here and will be available in Version 7.1 of the REFPROP database.

The transport property equations developed in this work are a combination of theoretical models for the dilute gas and the thermal conductivity critical enhancement, and empirical equations for the residual contribution resulting from the interaction between molecules. The equation for the dilute gas uses Chapman–Enskog theory with a collision integral fitted in this work to experimental data. The critical enhancement uses the simplified crossover model of Olchowy and Sengers [17]. The empirical equations for the residual contributions are similar to the terms used in typical Helmholtz energy equations of state (Lemmon et al. [14]). The number of terms was kept to a minimum to aid in the extrapolation of the equations to low and high temperatures and to high pressures and densities. Nonlinear fitting techniques similar to those employed in the development of the air and R-143a equations of state (Lemmon and Jacobsen [18]) were used here to derive the final equations.

The extrapolation of the equations for argon and nitrogen at very low temperatures was monitored carefully so that the resulting equations could be used in corresponding states applications for fluids with reduced triple point temperatures below those of nitrogen or argon. Graphs are included in Section 4 to illustrate the extrapolation behavior of the equations.

The transport properties of fluids at extremely low pressures may be quite different from those measured at “dilute” states. The dilute states of the gas are generally taken to be at a pressure of about one atmosphere, and most measurements of dilute gas transport properties are taken at this pressure. In this work, properties of the ideal gas at zero pressure are taken to be nearly identical to those of the dilute gas (minus any pressure dependence), and other literature should be consulted if actual gas properties are required at very low pressures. The thermal conductivity and viscosity equations presented here are not valid when the mean free path of the gas is comparable to the dimensions of the confining medium.

2. VISCOSITY AND THERMAL CONDUCTIVITY EQUATIONS

Several correlations are currently available that calculate the transport properties of nitrogen, argon, and oxygen. Viscosity and thermal conductivity equations are available in the work of Stephan and Krauss [19] for nitrogen, Laesecke et al. [20] for oxygen, Younglove and Hanley [21] for argon, and Younglove [22] for all three fluids. An equation for the thermal conductivity of air was reported by Stephan and Laesecke [23].

The transport property equations presented here use the independent properties temperature and density as input conditions. In most practical applications, including measured properties reported in the literature, the input conditions are temperature and pressure. Accurate equations of state for the pure fluids must be used to obtain the required density. The equations of state of Span et al. [24] for nitrogen, Tegeler et al. [25] for argon, Schmidt and Wagner [26] for oxygen, and Lemmon et al. [14] for air were used here for this purpose.

The viscosities of nitrogen, argon, oxygen, and air are expressed in this work using the equation,

$$\eta = \eta^0(T) + \eta^{\mathrm{r}}(\tau, \delta), \tag{1}$$

where η is the viscosity in μPa · s, η^0 is the dilute gas viscosity, η^{r} is the residual fluid viscosity, $\tau = T_{\mathrm{c}}/T$, and $\delta = \rho/\rho_{\mathrm{c}}$. The critical parameters T_{c} and ρ_{c} (taken from the thermodynamic equations of state referenced above) are given in Table I. Since the effects of the critical region behavior on viscosity are negligible for most practical states, no enhancement for the critical region viscosity was used in this work. The dilute gas contribution is given by

$$\eta^0(T) = \frac{0.0266958\sqrt{MT}}{\sigma^2 \Omega(T^*)}, \tag{2}$$

where σ is the Lennard-Jones size parameter and Ω is the collision integral, given by

$$\Omega(T^*) = \exp\left(\sum_{i=0}^{4} b_i [\ln(T^*)]^i\right),$$

where $T^* = T/(\varepsilon/k)$ and ε/k is the Lennard-Jones energy parameter. The Lennard-Jones parameters are given in Table I, and the coefficients b_i (fitted in this work to the experimental data) are given in Table II. The residual fluid contribution to the viscosity is given (in μPa · s) by

$$\eta^{\mathrm{r}}(\tau, \delta) = \sum_{i=1}^{n} N_i \tau^{t_i} \delta^{d_i} \exp(-\gamma_i \delta^{l_i}), \tag{3}$$

Table I. Parameters of the Viscosity and Thermal Conductivity Equations

Parameter	Nitrogen	Argon	Oxygen	Air
T_c (K)	126.192	150.687	154.581	132.6312[a]
ρ_c ($\mathrm{mol \cdot dm^{-3}}$)	11.1839	13.40743	13.63	10.4477[a]
p_c (MPa)	3.3958	4.863	5.043	3.78502[a]
M ($\mathrm{g \cdot mol^{-1}}$)	28.01348	39.948	31.9988	28.9586
ε/k (K)	98.94	143.2[b]	118.5	103.3
σ (nm)	0.3656	0.335[b]	0.3428	0.360
ξ_0 (nm)	0.17	0.13	0.24	0.11
Γ	0.055	0.055	0.055	0.055
q_D (nm)	0.40	0.32	0.51	0.31
T_{ref} (K)	252.384	301.374	309.162	265.262

[a] The values given for air are the values at the maxcondentherm.
[b] Lennard-Jones parameters taken from Aziz [33].

where γ_i is zero when l_i is zero and one when l_i is not zero. The coefficients and exponents of this equation are given in Table III.

Similar to the model for viscosity, the thermal conductivities of nitrogen, argon, oxygen, and air are expressed as functions of temperature and density:

$$\lambda = \lambda^0(T) + \lambda^{\mathrm{r}}(\tau, \delta) + \lambda^{\mathrm{c}}(\tau, \delta), \tag{4}$$

where λ is the thermal conductivity in $\mathrm{mW \cdot m^{-1} \cdot K^{-1}}$, λ^0 is the dilute gas thermal conductivity, λ^{r} is the residual fluid thermal conductivity, λ^{c} is the thermal conductivity critical enhancement, $\tau = T_c/T$, and $\delta = \rho/\rho_c$. The critical parameters T_c and ρ_c are given in Table I. The dilute gas contribution is given by

$$\lambda^0 = N_1 \left[\frac{\eta^0(T)}{1\ \mu\mathrm{Pa \cdot s}} \right] + N_2 \tau^{t_2} + N_3 \tau^{t_3}, \tag{5}$$

Table II. Coefficients of the Collision Integral Equation

i	b_i
0	0.431
1	−0.4623
2	0.08406
3	0.005341
4	−0.00331

Table III. Coefficients and Exponents of the Residual Fluid Viscosity Equations

i	N_i	t_i	d_i	l_i
		Nitrogen		
1	10.72	0.1	2	0
2	0.03989	0.25	10	1
3	0.001208	3.2	12	1
4	−7.402	0.9	2	2
5	4.620	0.3	1	3
		Argon		
1	12.19	0.42	1	0
2	13.99	0.0	2	0
3	0.005027	0.95	10	0
4	−18.93	0.5	5	2
5	−6.698	0.9	1	4
6	−3.827	0.8	2	4
		Oxygen		
1	17.67	0.05	1	0
2	0.4042	0.0	5	0
3	0.0001077	2.10	12	0
4	0.3510	0.0	8	1
5	−13.67	0.5	1	2
		Air		
1	10.72	0.2	1	0
2	1.122	0.05	4	0
3	0.002019	2.4	9	0
4	−8.876	0.6	1	1
5	−0.02916	3.6	8	1

where η^0 is the dilute gas viscosity described previously. The coefficients and exponents are given in Table IV. The residual contribution to the thermal conductivity is given (in $\mathrm{mW \cdot m^{-1} \cdot K^{-1}}$) by

$$\lambda^{\mathrm{r}} = \sum_{i=4}^{n} N_i \tau^{t_i} \delta^{d_i} \exp(-\gamma_i \delta^{l_i}), \tag{6}$$

where γ_i is zero when l_i is zero and one when l_i is not zero. The coefficients and exponents of this equation are given in Table IV.

Table IV. Coefficients and Exponents of the Residual Fluid Thermal Conductivity Equations

i	N_i	t_i	d_i	l_i
		Nitrogen		
1	1.511			
2	2.117	−1.0		
3	−3.332	−0.7		
4	8.862	0.0	1	0
5	31.11	0.03	2	0
6	−73.13	0.2	3	1
7	20.03	0.8	4	2
8	−0.7096	0.6	8	2
9	0.2672	1.9	10	2
		Argon		
1	0.8158			
2	−0.4320	−0.77		
3	0.0	−1.0		
4	13.73	0.0	1	0
5	10.07	0.0	2	0
6	0.7375	0.0	4	0
7	−33.96	0.8	5	2
8	20.47	1.2	6	2
9	−2.274	0.8	9	2
10	−3.973	0.5	1	4
		Oxygen		
1	1.036			
2	6.283	−0.9		
3	−4.262	−0.6		
4	15.31	0.0	1	0
5	8.898	0.0	3	0
6	−0.7336	0.3	4	0
7	6.728	4.3	5	2
8	−4.374	0.5	7	2
9	−0.4747	1.8	10	2
		Air		
1	1.308			
2	1.405	−1.1		
3	−1.036	−0.3		
4	8.743	0.1	1	0
5	14.76	0.0	2	0
6	−16.62	0.5	3	2
7	3.793	2.7	7	2
8	−6.142	0.3	7	2
9	−0.3778	1.3	11	2

The thermal conductivity critical enhancement model of Olchowy and Sengers [17] was used to calculate the fluid properties in the critical region. The equations of Olchowy and Sengers are repeated here for completeness:

$$\lambda^{\mathrm{c}} = \rho c_{\mathrm{p}} \frac{k R_0 T}{6\pi\xi\eta(T,\rho)} (\tilde{\Omega} - \tilde{\Omega}_0), \tag{7}$$

where

$$\tilde{\Omega} = \frac{2}{\pi}\left[\left(\frac{c_{\mathrm{p}} - c_{\mathrm{v}}}{c_{\mathrm{p}}}\right)\tan^{-1}(\xi/q_D) + \frac{c_{\mathrm{v}}}{c_{\mathrm{p}}}(\xi/q_D)\right] \quad \text{and} \tag{8}$$

$$\tilde{\Omega}_0 = \frac{2}{\pi}\left\{1 - \exp\left[\frac{-1}{(\xi/q_D)^{-1} + \frac{1}{3}(\xi/q_D)^2 (\rho_{\mathrm{c}}/\rho)^2}\right]\right\}. \tag{9}$$

The correlation length ξ is given by

$$\xi = \xi_0 \left[\frac{\tilde{\chi}(T,\rho) - \tilde{\chi}(T_{\mathrm{ref}},\rho)\frac{T_{\mathrm{ref}}}{T}}{\Gamma}\right]^{\nu/\gamma}, \tag{10}$$

where

$$\tilde{\chi}(T,\rho) = \frac{p_{\mathrm{c}}\rho}{\rho_{\mathrm{c}}^2}\left(\frac{\partial \rho}{\partial p}\right)_T. \tag{11}$$

In these equations, k is Boltzmann's constant ($1.380658 \times 10^{-23}\ \mathrm{J \cdot K^{-1}}$), and R_0, ν, and γ are theoretically based constants with values of $R_0 = 1.01$, $\nu = 0.63$, and $\gamma = 1.2415$. The terms q_D, ξ_0, and Γ are fluid-specific (fitted) terms, and T_{ref} is a reference temperature that is significantly above the critical temperature (in this work, T_{ref} was taken as twice the critical temperature). The values of these terms are given in Table I. The value of λ_{c} should be set to zero when the bracketed term in Eq. (10) is negative (usually at high temperatures) or zero. The isochoric heat capacity (c_{v}), isobaric heat capacity (c_{p}), and the first derivative of density with respect to pressure are calculated from the equation of state at the specified temperature and density.

Calculated values of the viscosity and thermal conductivity are given in Table V for use in verifying computer programs developed using the equations given above. The additional digits do not reflect the accuracy of the equations but are given as an aid for program verification.

Table V. Viscosity and Thermal Conductivity Values Calculated from the Equations

Temperature (K)	Density ($\mathrm{mol \cdot dm^{-3}}$)	Viscosity ($\mathrm{\mu Pa \cdot s}$)	Thermal conductivity ($\mathrm{mW \cdot m^{-1} \cdot K^{-1}}$)
		Nitrogen	
100.0	0.0[a]	6.90349	9.27749
300.0	0.0[a]	17.8771	25.9361
100.0	25.0	79.7418	103.834
200.0	10.0	21.0810	36.0099
300.0	5.0	20.7430	32.7694
126.195	11.18	18.2978	675.800
		Argon	
100.0	0.0[a]	8.18940	6.36587
300.0	0.0[a]	22.7241	17.8042
100.0	33.0	184.232	111.266
200.0	10.0	25.5662	26.1377
300.0	5.0	26.3706	23.2302
150.69	13.4	27.6101	856.793
		Oxygen	
100.0	0.0[a]	7.70243	8.94334
300.0	0.0[a]	20.6307	26.4403
100.0	35.0	172.136	146.044
200.0	10.0	22.4445	34.6124
300.0	5.0	23.7577	32.5491
154.6	13.6	24.7898	377.476
		Air	
100.0	0.0[a]	7.09559	9.35902
300.0	0.0[a]	18.5230	26.3529
100.0	28.0	107.923	119.221
200.0	10.0	21.1392	35.3185
300.0	5.0	21.3241	32.6062
132.64	10.4	17.7623	75.6231

[a] Dilute gas values at zero density.

3. EXPERIMENTAL DATA AND COMPARISONS TO THE EQUATIONS

A comprehensive search was made to obtain the experimental data available in the open literature. Table VI gives the sources of experimental data, the temperature, pressure, and density ranges, the number of points, and the average absolute deviations (AAD) between the experimental data and the equations presented here. Literature sources with only three or

Table VI. Summary of Experimental Data and Comparisons with the Equations

Author	No. Points	Temperature range (K)	Pressure range (MPa)	Density range ($\mathrm{mol \cdot dm^{-3}}$)	AAD (%)
		Nitrogen-viscosity			
Baron et al. (1959) [36]	40	325–408	0.68–55.2	0.20–14.5	1.38
Bonilla et al. (1951) [38]	25	200–2500	0.1	Dilute Gas	4.60
Boon et al. (1967) [40]	4	68.1–70.2	0.83	30–30.3	10.3
Boyd (1930) [43]	68	303–343	7.13–19.4	2.46–6.87	5.72
Chierici and Paratella (1969) [51]	6	323	0.6–30.5	0.22–9.83	0.54
Clarke and Smith (1968) [52]	12	114–375	0.1	Dilute Gas	0.58
Clarke and Smith (1969) [53]	13	120–360	0.001	Dilute Gas	0.22
Dawe and Smith (1970) [58]	25	293–1530	0.1	Dilute Gas	0.77
Diller (1983) [65]	65	90–300	0.36–33.6	0.68–29.6	1.25
DiPippo and Kestin (1968) [66]	30	295–456	0.03–0.17	Dilute Gas	0.15
DiPippo et al. (1966) [67]	24	296–773	0.01–0.17	Dilute Gas	0.27
DiPippo et al. (1968) [68]	5	303	0.1–2.34	0.04–0.93	0.03
Ellis and Raw (1959) [70]	7	973–1270	0.1	Dilute Gas	5.41
Evers et al. (2002) [71]	76	233–523	0.09–29.7	0.03–10.7	0.08
Filippova and Ishkin (1962) [74]	27	90.2–273	3.5–15.1	3.58–28.2	8.71
Flynn et al. (1963) [76]	34	195–373	0.68–17.9	0.27–12.8	0.28
Forster (1963) [77]	10	65.6–121	0.01–2.65	18.1–30.6	10.3
Gerf and Galkov (1940) [81]	7	66.2–77.3	0.02–0.1	28.8–30.5	3.48
Goldman (1963) [83]	16	195–298	5.17–12.7	3.17–9.58	1.11
Golubev and Kurin (1974) [84]	76	273–423	9.81–401	2.68–30.5	1.82
Golubev (1970) [89]	94	273–523	0.1–81.1	0.02–18.8	1.38
Gough et al. (1976) [91]	11	120–320	0.1	Dilute Gas	0.41
Gracki et al. (1969) [92]	46	183–298	0.53–25.7	0.27–12.8	0.65
Grevendonk et al. (1970) [95]	134	66.5–123	0.59–19.5	17.9–31.3	3.20
Guevara et al. (1969) [97]	23	283–2150	0.1	Dilute Gas	0.32
Hellemans et al. (1970) [106]	44	96.7–125	0.61–9.85	15.8–26.7	8.48
Hoogland et al. (1985) [110]	15	298–333	0.2–11.7	0.07–4.67	0.12
Iwasaki and Kestin (1963) [116]	32	293–298	0.1–9.98	0.04–4.01	0.13
Iwasaki (1954) [117]	25	298–423	2.09–19	0.59–7.21	0.55
Johnston and McCloskey (1940) [127]	37	90.2–300	0.1	Dilute Gas	0.21
Johnston et al. (1951) [128]	16	78.6–306	0.001–0.07	Dilute Gas	0.32
Kao and Kobayashi (1967) [132]	35	183–323	1.01–50.7	0.37–17.3	0.75
Kestin and Wang (1958) [135]	13	298	0.1–10.1	0.04–4.07	0.21
Kestin and Yata (1968) [136]	6	303	0.1–2.38	0.04–0.94	0.03
Kestin and Whitelaw (1963) [138]	37	344–539	0.12–14.8	0.02–4.63	0.90
Kestin and Ro (1976) [139]	9	298–1270	0.1	Dilute Gas	0.19
Kestin and Leidenfrost (1959) [141]	20	293–298	0.01–7	0.006–2.83	0.16
Kestin and Leidenfrost (1959) [142]	14	293–296	0.1–15.5	0.04–6.2	0.17
Kestin et al. (1971) [144]	33	298	0.1–10.7	0.04–4.28	0.10
Kestin et al. (1977) [146]	9	298–673	0.1	Dilute Gas	0.29
Kestin et al. (1982) [148]	5	298–473	0.1	Dilute Gas	0.05
Kestin et al. (1972) [149]	8	298–973	0.1	Dilute Gas	0.17
Kestin et al. (1972) [152]	6	298–973	0.1	Dilute Gas	0.14

Table VI. *(Continued)*

Author	No. Points	Temperature range (K)	Pressure range (MPa)	Density range ($\mathrm{mol \cdot dm^{-3}}$)	AAD (%)
Kobayashi and Kurase (1977) [161]	6	298	0.11–4.02	0.04–1.63	0.34
Lavushchev and Lyusternik (1978) [165]	54	375–1990	0.1	Dilute Gas	0.28
Lazarre and Vodar (1957) [167]	21	298–348	0.09–319	0.03–29.5	1.47
Lukin et al. (1983) [176]	23	76.5–293	0.09–0.1	Dilute Gas	0.20
Maitland and Smith (1972) [177]	28	100–2000	0.1	Dilute Gas	0.17
Maitland and Smith (1974) [178]	24	394–1550	0.1	Dilute Gas	0.83
Maitland et al. (1983) [179]	4	301–378	0.1	Dilute Gas	0.31
Makavetskas et al. (1963) [180]	70	285–933	1.53–60.7	0.23–16.7	2.49
Makita (1957) [181]	54	299–473	0.1–78.5	0.02–18.5	1.62
Matthews et al. (1976) [185]	15	120–1700	0.1	Dilute Gas	0.72
Michels and Gibson (1932) [187]	56	298–348	1.11–97.9	0.44–20.3	0.25
Reynes and Thodos (1966) [211]	30	373–473	7.14–69.4	1.76–14.8	1.99
Rigby and Smith (1966) [214]	15	293–973	0.1	Dilute Gas	1.97
Ross and Brown (1957) [219]	41	223–298	3.45–68.9	1.4–21.3	2.51
Rudenko and Schubnikow (1934) [221]	8	63.9–77.3	0.01–0.1	28.8–30.8	1.19
Rudenko (1939) [222]	6	77.4–112	0.1–1.62	21.7–28.8	19.1
Rutherford (1984) [223]	15	298	0.44–6.99	0.17–2.83	0.17
Schlumpf et al. (1975) [231]	11	323	10–300	3.66–28.3	0.51
Shepeleva and Golubev (1968) [238]	64	80.5–278	0.92–50.6	0.42–31.5	4.51
Timrot et al. (1969) [252]	8	300–650	0.1	Dilute Gas	0.33
Timrot et al. (1974) [253]	31	295–573	0.09–11.8	0.02–4.56	0.25
Trautz and Melster (1930) [256]	4	301–550	0.1	Dilute Gas	1.50
Trautz and Heberling (1931) [257]	9	293–524	0.1	Dilute Gas	1.54
Trautz and Zink (1930) [258]	33	482–1100	0.1	Dilute Gas	4.13
van Itterbeek et al. (1966) [267]	33	70.1–90.2	0.09–2.4	26.6–30.1	1.35
van Itterbeek et al. (1966) [268]	38	70–90.1	0.05–9.93	26.6–30.6	2.04
Vermesse (1969) [274]	89	273–370	10.7–651	3.36–35.3	1.24
Vermesse et al. (1963) [275]	24	299–322	54.9–488	15.5–32.3	2.08
Vogel (1984) [277]	10	297–640	0.1	Dilute Gas	0.26
Vogel et al. (1989) [278]	44	299–689	0.03–0.16	Dilute Gas	0.27
Wobser and Muller (1941) [283]	5	293–371	0.1	Dilute Gas	0.57
Yen (1919) [284]	21	296	0.1	Dilute Gas	0.35
Zozulya and Blagoi (1974) [291]	122	126–135	3.32–6.39	6.89–16.1	5.50
Nitrogen-thermal conductivity					
Assael and Wakeham (1981) [31]	18	307–309	1.07–9.31	0.41–3.62	0.31
Borovik (1947) [41]	21	90.4–171	1.13–10	2.62–27	6.04
Borovik et al. (1940) [42]	4	77.9–112	0.1–1.62	21.7–28.7	4.84
Brain (1967) [44]	14	420–553	0.1	Dilute Gas	1.71
Chen and Saxena (1973) [49]	231	373–2470	0.01–0.04	Dilute Gas	1.24
Clifford et al. (1979) [54]	34	300–303	0.58–35.6	0.23–11.9	0.40
Clifford et al. (1981) [55]	41	341–388	0.52–26.5	0.17–7.87	0.38
Duan et al. (1997) [69]	10	297	0.43–2.06	0.17–0.83	0.76
Faubert and Springer (1972) [72]	13	800–2000	0.1	Dilute Gas	3.61
Franck (1951) [78]	18	93–676	0.009–0.04	Dilute Gas	3.04

Table VI. *(Continued)*

Author	No. Points	Temperature range (K)	Pressure range (MPa)	Density range ($\mathrm{mol \cdot dm^{-3}}$)	AAD (%)
Geier and Schafer (1961) [80]	12	273–1370	0.1	Dilute Gas	4.59
Golubev and Kalzsina (1964) [85]	322	77.4–273	0.1–50.7	0.04–31.8	3.64
Gray and Wright (1961) [93]	4	298–422	0.1	Dilute Gas	0.31
Gregory and Marshall (1928) [94]	152	282–299	0.005–0.11	Dilute Gas	1.55
Haarman (1973) [98]	8	328–468	0.1	Dilute Gas	0.49
Hammann (1938) [99]	6	64.7–73.5	0.1	29.4–30.7	22.7
Haran et al. (1983) [102]	45	308–429	0.45–10.1	0.17–3.91	0.82
Imaishi et al. (1984) [113]	19	300	0.76–12.1	0.30–4.79	0.29
Johannin and Vodar (1957) [121]	50	348–573	0.1–132	0.02–18.7	1.65
Johannin (1958) [122]	71	348–974	0.1–164	0.01–18.4	2.16
Johns et al. (1988) [123]	12	472–475	1.01–27.7	0.25–6.15	0.70
Johns et al. (1986) [124]	14	426–478	1.01–29.6	0.25–7.19	0.84
Keyes and Sandell (1950) [154]	41	274–674	0.1–15.4	0.01–6.27	5.69
Keyes and Vines (1965) [155]	21	125–202	1.7–13.6	1.05–22.3	1.87
Keyes (1955) [157]	4	92.1–273	0.1–1.07	0.13–0.57	1.03
Keyes (1951) [158]	13	273–423	0.1–14.5	0.02–5.68	1.65
Le Neindre (1972) [168]	118	298–801	0.1–100	0.01–20.5	1.14
Le Neindre et al. (1968) [169]	50	297–305	0.1–119	0.04–21.7	0.77
Lenoir and Comings (1951) [172]	13	314	0.1–20.8	0.03–7.44	0.65
Lenoir et al. (1953) [173]	13	326	0.1–22	0.03–7.46	0.87
Maitland et al. (1983) [179]	4	301–378	0.1	Dilute Gas	0.31
Michels and Botzen (1953) [186]	82	298–348	0.1–252	0.03–26.2	5.90
Misic and Thodos (1965) [193]	21	295–324	6.2–31.9	2.54–11.2	1.17
Mostert et al. (1990) [194]	20	308	1.11–20.1	0.43–7.37	1.16
Moszynski and Singh (1973) [196]	46	323–348	0.1–150	0.03–22	1.25
Nuttall and Ginnings (1957) [203]	60	323–780	0.07–10.1	0.01–3.7	3.75
Pereira and Raw (1963) [205]	5	305–453	0.1	Dilute Gas	1.25
Perkins et al. (1991) [5]	72	425–428	3.26–67.5	0.90–13.1	0.72
Perkins et al. (1991) [6]	377	81–303	0.33–71.1	0.37–32.1	0.67
Powers et al. (1954) [207]	12	68.7–88.1	0.03–0.3	26.9–30.1	3.76
Richard and Shankland (1989) [213]	6	310–352	0.0	Dilute Gas	0.37
Roder (1981) [215]	93	297–309	1.43–69.1	0.57–17.5	1.01
Rothman and Bromley (1955) [220]	4	639–952	0.1	Dilute Gas	1.29
Saxena and Chen (1975) [228]	66	338–2520	0.1	Dilute Gas	2.27
Schafer and Reiter (1957) [229]	12	273–1370	0.0	Dilute Gas	5.98
Schottky (1952) [232]	9	373–773	0.1	Dilute Gas	5.22
Schramm (1964) [233]	10	276–1400	0.1	Dilute Gas	2.39
Slyusar et al. (1975) [240]	31	64.2–300	0.01–294	0.16–30.8	12.8
Stolyarov et al. (1950) [243]	23	286–571	0.09–49	0.02–15.2	5.09
Tufeu and Le Neindre (1980) [261]	13	298	0.1–1000	0.04–39	0.88
Tufeu and Le Neindre (1979) [262]	22	481–748	0.06–18.7	0.01–3.63	9.77
Uhlir (1952) [263]	22	76.4–184	0.58–6.88	3.26–29.4	3.91
Vargaftik and Zimina (1964) [270]	11	304–1140	0.1	Dilute Gas	1.21
Vines (1960) [276]	4	533–1170	0.1	Dilute Gas	0.97
Westenberg and deHaas (1962) [280]	4	300–1000	0.1	Dilute Gas	1.51

Table VI. *(Continued)*

Author	No. Points	Temperature range (K)	Pressure range (MPa)	Density range (mol·dm^{-3})	AAD (%)
Yorizane et al. (1983) [285]	28	299–323	0.1–15	0.03–5.9	0.74
Zheng et al. (1984) [287]	18	298	0.1–15.6	0.04–6.11	0.87
Ziebland and Burton (1958) [289]	86	80.7–203	0.1–13.6	0.06–28.5	3.54
Ziebland and Marsh (1977) [290]	41	80–1400	0.1	Dilute Gas	0.85
Argon-viscosity					
Abachi et al. (1980) [27]	18	83.8–90	0.06–0.13	34.5–35.5	2.09
Baharudin et al. (1975) [34]	6	85.7–110	0.08–0.64	31.2–35.2	5.43
Bonilla et al. (1951) [38]	25	200–2500	0.1	Dilute Gas	4.84
Boon and Thomaes (1963) [39]	6	84–89	0.07–0.12	34.7–35.4	1.06
Boon et al. (1967) [40]	6	84–89	0.07–0.12	34.7–35.4	0.50
Clarke and Smith (1968) [52]	12	114–375	0.1	Dilute Gas	0.52
Clifford et al. (1975) [56]	9	321–1300	0.1	Dilute Gas	0.51
Dawe and Smith (1970) [58]	44	292–1530	0.1	Dilute Gas	0.66
de Bock et al. (1967) [59]	19	90	0.13–13.5	34.5–35.5	2.39
de Bock et al. (1967) [60]	72	88.5–140	0.39–19.6	24–36	4.71
De Rocco and Halford (1958) [63]	20	211–471	0.1	Dilute Gas	0.65
DiPippo and Kestin (1968) [66]	23	297–575	0.03–0.17	Dilute Gas	0.43
DiPippo et al. (1968) [68]	10	293–303	0.1–2.34	0.04–0.96	0.13
Evers et al. (2002) [71]	81	233–523	0.09–28.1	0.02–6.07	0.23
Filippova and Ishkin (1959) [73]	31	90.2–273	0.09–14.7	0.04–35.5	6.30
Filippova and Ishkin (1962) [74]	52	90.2–273	3.6–15.3	1.78–35.5	10.2
Flynn et al. (1963) [76]	27	195–373	2.92–18.8	1.2–17.4	0.23
Forster (1963) [77]	8	85.4–114	0.08–0.84	30.4–35.2	3.48
Golubev (1970) [89]	49	273–473	0.1–48.1	0.02–17	3.15
Gough et al. (1976) [91]	11	120–320	0.1	Dilute Gas	0.37
Gracki et al. (1969) [92]	47	173–298	0.46–17.1	0.25–21	1.09
Guevara et al. (1969) [97]	22	283–2100	0.1	Dilute Gas	0.65
Haynes (1973) [103]	167	85–298	0.07–34.5	0.06–35.3	0.92
Hellemans et al. (1970) [105]	44	105–147	0.46–9.81	20.1–33.1	8.38
Hellemans et al. (1974) [108]	8	298–973	0.1	Dilute Gas	0.43
Hobley et al. (1989) [109]	5	301–521	0.1	Dilute Gas	0.19
Iwasaki and Kestin (1963) [116]	14	293–303	0.1–5.26	0.04–2.21	0.15
Iwasaki et al. (1964) [119]	14	293–303	0.1–5.26	0.04–2.21	0.15
Johnston and Grilly (1942) [126]	42	90.3–296	0.1	Dilute Gas	0.56
Kalelkar and Kestin (1970) [129]	9	298–1120	0.1	Dilute Gas	0.43
Kestin and Nagashima (1964) [134]	20	293–303	0.1–5.18	0.04–2.18	0.23
Kestin and Wang (1958) [135]	13	298	0.1–10.1	0.04–4.29	0.21
Kestin and Whitelaw (1963) [138]	47	295–538	0.12–14.2	0.02–5.13	1.64
Kestin and Ro (1976) [139]	9	298–1270	0.01	Dilute Gas	0.27
Kestin and Ro (1982) [140]	5	298–473	0.1	Dilute Gas	0.59
Kestin and Leidenfrost (1959) [141]	15	293–298	0.03–3.12	0.01–1.31	0.07
Kestin and Wakeham (1979) [143]	5	301–473	0.1	Dilute Gas	0.58
Kestin et al. (1971) [144]	40	298	0.1–10.1	0.04–4.29	0.27
Kestin et al. (1978) [145]	9	298–773	0.1	Dilute Gas	0.31

Table VI. *(Continued)*

Author	No. Points	Temperature range (K)	Pressure range (MPa)	Density range ($\mathrm{mol \cdot dm^{-3}}$)	AAD (%)
Kestin et al. (1972) [150]	7	298–973	0.1	Dilute Gas	0.29
Kestin et al. (1972) [151]	8	298–973	0.1	Dilute Gas	0.50
Kestin et al. (1970) [153]	8	298–973	0.1	Dilute Gas	0.26
Kiyama and Makita (1952) [159]	40	323–573	0.1–9.97	0.02–3.76	1.81
Kurin and Golubev (1974) [163]	104	273–423	9.81–380	2.76–34.9	1.44
Lowry et al. (1964) [175]	20	102–128	5.07–50.7	28.1–36.1	9.18
Lukin et al. (1983) [176]	21	93.2–293	0.1	Dilute Gas	0.47
Maitland and Smith (1972) [177]	28	100–2000	0.1	Dilute Gas	0.18
Maitland and Smith (1974) [178]	11	295–1530	0.1	Dilute Gas	0.45
Makita (1957) [181]	45	298–423	0.1–78.5	0.02–22	0.84
Makita (1955) [182]	30	323–573	0.1–10.1	0.02–3.87	2.04
Malbrunot et al. (1983) [183]	9	83.9–97	0.06–0.25	33.4–35.5	2.66
Michels et al. (1954) [189]	96	273–348	0.92–202	0.41–28.9	0.25
Mostert et al. (1989) [195]	25	174	16.1–471	20.7–42	5.05
Naugle (1966) [200]	4	84–112	0.81	30.7–35.5	1.07
Naugle et al. (1966) [201]	59	85–146	1.27–15.6	26.6–35.5	11.1
Rabinovich et al. (1976) [209]	63	298–523	2.56–58.9	0.58–19.1	0.64
Reynes and Thodos (1964) [212]	35	373–473	7.14–83	1.79–18	4.28
Rigby and Smith (1966) [214]	15	293–973	0.1	Dilute Gas	2.15
Rudenko and Schubnikow (1934) [221]	4	84.2–87.3	0.07–0.1	34.9–35.4	2.75
Saji and Okuda (1965) [224]	5	84.1–86.9	0.07–0.09	35–35.4	0.47
Timrot et al. (1969) [252]	7	300–600	0.1	Dilute Gas	0.59
Timrot et al. (1975) [254]	39	292–575	0.09–14.4	0.02–6.06	0.39
Trappeniers et al. (1980) [255]	44	223–323	99.9–897	23–44.5	5.08
Trautz and Zink (1930) [258]	22	567–1100	0.1	Dilute Gas	3.87
van der Gulik and Trappeniers (1986) [264]	25	174	16.1–471	20.7–42	4.79
van Itterbeek et al. (1966) [268]	16	84.3–89.9	0.1–9.79	34.5–35.5	0.90
Vermesse and Vidal (1973) [273]	25	308	12–606	4.88–39.9	2.33
Vogel (1984) [277]	10	294–668	0.1	Dilute Gas	0.21
Wilhelm and Vogel (2000) [282]	160	298–423	0.09–20.1	0.02–8.49	0.12
Wobser and Muller (1941) [283]	5	293–371	0.1	Dilute Gas	0.49
Zhdanova (1957) [286]	14	84.3–149	0.07–4.56	18.4–35.4	6.39
		Argon-thermal conductivity			
Amirkhanov et al. (1972) [29]	140	113–253	9.81–98.1	5.21–37.1	2.62
Amirkhanov et al. (1970) [30]	220	282–624	9.81–98.1	1.84–25	2.24
Assael et al. (1981) [32]	27	308	0.95–10.9	0.37–4.41	0.32
Bailey and Kellner (1968) [35]	405	88.6–299	0.09–49	0.04–36.5	3.19
Brain (1967) [44]	18	419–553	0.1	Dilute Gas	1.68
Calado et al. (1987) [46]	70	107–131	0.54–10.4	26.7–32.4	0.64
Chen and Saxena (1975) [50]	88	338–2520	0.02–0.09	Dilute Gas	0.70
Clifford et al. (1981) [55]	73	311–377	0.65–17.4	0.24–5.9	0.37
Correia et al. (1968) [57]	24	276–1250	0.1	Dilute Gas	1.36
de Castro and Roder (1981) [61]	112	297–309	1.46–68.7	0.58–20.7	0.97
de Groot et al. (1978) [62]	120	298–302	0.59–32.1	0.23–12.8	1.40

Table VI. *(Continued)*

Author	No. Points	Temperature range (K)	Pressure range (MPa)	Density range ($mol \cdot dm^{-3}$)	AAD (%)
Faubert and Springer (1972) [72]	13	800–2000	0.1	Dilute Gas	0.94
Gambhir et al. (1967) [79]	4	309–364	0.01	Dilute Gas	2.76
Haarman (1973) [98]	8	328–468	0.1	Dilute Gas	0.79
Hammerschmidt (1995) [100]	5	303–463	0.1	Dilute Gas	0.83
Hansen et al. (1995) [101]	14	332–646	0.1	Dilute Gas	1.65
Haran et al. (1983) [102]	49	308–429	0.8–10.2	0.22–3.93	0.53
Ikenberry and Rice (1963) [112]	62	91–235	0.1–53.9	0.06–35.9	2.86
Irving et al. (1973) [114]	4	273–448	0.1	Dilute Gas	0.20
Johns et al. (1986) [124]	22	427–473	1.04–24.8	0.29–6.62	0.87
Kestin et al. (1980) [147]	32	301	0.6–35.3	0.24–13.7	0.45
Kestin et al. (1972) [150]	8	298–973	0.1	Dilute Gas	0.05
Keyes and Vines (1965) [155]	8	162–196	4.79–12.2	3.88–17.9	2.94
Keyes (1954) [156]	10	363–623	0.1–1.98	0.02–0.65	1.08
Keyes (1955) [157]	16	86.9–273	0.03–1.11	0.03–35.1	1.81
Le Neindre (1972) [168]	177	298–977	0.1–100	0.01–24.3	1.00
Le Neindre et al. (1969) [170]	378	294–978	0.1–128	0.01–26.2	0.91
Le Neindre et al. (1989) [171]	11	298	0.1–1000	0.04–44.9	1.86
Lenoir and Comings (1951) [172]	9	314	0.1–19.7	0.03–7.76	1.75
Lenoir et al. (1953) [173]	16	326	0.1–22	0.03–8.23	1.81
Mardolcar et al. (1986) [184]	54	107–429	0.61–10.1	0.17–32.5	0.48
Michels et al. (1956) [188]	82	273–348	0.1–243	0.03–30.6	14.9
Michels et al. (1963) [190]	110	274–348	0.1–246	0.03–30.4	0.76
Millat et al. (1987) [191]	77	308–428	0.58–10.9	0.22–3.7	0.65
Millat et al. (1989) [192]	61	174–309	0.36–9.68	0.20–8.3	0.66
Moszynski and Singh (1973) [196]	105	323–473	0.1–162	0.02–26.9	1.24
Patek and Klomfar (2002) [204]	170	299–426	0.15–15.7	0.04–6.45	1.11
Perkins et al. (1991) [5]	144	299–303	2.6–65.5	1.05–20.1	0.95
Perkins et al. (1991) [8]	84	103–324	0.19–11.4	0.20–4.87	0.68
Roder et al. (1988) [7]	1484	102–326	0.19–67.9	0.09–36	1.12
Roder et al. (2000) [9]	718	301–344	0.16–8.33	0.05–3.21	0.80
Rosenbaum et al. (1966) [218]	48	279–322	2.65–71.3	1.11–21.9	1.90
Saxena and Saxena (1968) [227]	12	373–1470	0.1	Dilute Gas	0.47
Schafer and Reiter (1957) [229]	12	273–1370	0.1	Dilute Gas	1.93
Schottky (1952) [232]	9	373–773	0.1	Dilute Gas	1.72
Schramm (1964) [233]	19	276–1400	0.1	Dilute Gas	0.73
Senftleben (1964) [236]	8	273–673	0.1	Dilute Gas	2.43
Shashkov et al. (1976) [237]	13	93.6–271	0.1	Dilute Gas	0.94
Slyusar et al. (1977) [239]	24	90–146	0.13–4.05	0.18–34.5	7.55
Smiley (1957) [241]	12	1100–3300	0.1	Dilute Gas	1.80
Springer and Wingeier (1973) [242]	9	900–2500	0.1	Dilute Gas	0.80
Sun et al. (2002) [244]	236	297–328	0.81–62.3	0.29–19.8	0.71
Sun et al. (2002) [245]	436	296–428	0.33–63.1	0.13–19.7	0.33
Tarzimanov and Arslanov (1971) [248]	47	298–654	0.09–196	0.02–30.3	1.61
Tiesinga et al. (1994) [251]	142	151–175	0.08–18.8	0.06–24.3	5.34
Uhlir (1952) [263]	65	86.6–194	0.09–9.74	0.06–35.2	4.13

Table VI. *(Continued)*

Author	No. Points	Temperature range (K)	Pressure range (MPa)	Density range ($mol \cdot dm^{-3}$)	AAD (%)
Vargaftik and Zimina (1964) [271]	69	273–1270	0.1	Dilute Gas	1.49
Vines (1960) [276]	4	533–1170	0.1	Dilute Gas	1.53
Yorizane et al. (1983) [285]	42	298–324	0.1–19.7	0.03–7.71	1.06
Zheng et al. (1984) [287]	20	298	0.1–17.5	0.04–7.45	1.18
Ziebland and Burton (1958) [289]	119	93.3–196	0.1–12.2	0.06–34.9	2.02
Ziebland and Marsh (1977) [290]	53	100–2000	0.1	Dilute Gas	0.33
Oxygen-viscosity					
Bonilla et al. (1951) [38]	25	200–2500	0.1	Dilute Gas	3.62
Boon and Thomaes (1963) [39]	8	75.4–91.6	0.01–0.11	35.4–37.9	1.27
Boon et al. (1967) [40]	8	75.4–91.6	1.14–1.21	35.5–37.9	4.29
Clifford et al. (1975) [56]	9	321–1300	0.1	Dilute Gas	0.39
de Bock et al. (1967) [59]	17	77	0.2–13.4	37.7–38.3	6.92
Golubev (1970) [89]	36	288–373	0.1–70.9	0.03–21.7	1.21
Grevendonk et al. (1968) [96]	92	77.7–150	0.78–19.2	23.1–38.5	4.34
Haynes (1977) [104]	197	75–300	0.01–34.6	0.11–37.9	1.3
Hellemans et al. (1970) [106]	49	96–152	0.18–9.86	19.5–35.4	10.2
Hellemans et al. (1973) [107]	12	298–770	0.1	Dilute Gas	0.97
Johnston and McCloskey (1940) [127]	35	90.3–300	0.1	Dilute Gas	0.37
Kestin and Yata (1968) [136]	12	293–303	0.1–2.51	0.04–1.04	0.19
Kestin and Leidenfrost (1959) [141]	15	293–298	0.01–5.26	0.005–2.19	0.22
Kestin and Leidenfrost (1959) [142]	11	293–296	0.1–9.28	0.04–3.99	0.23
Kiyama and Makita (1952) [159]	35	274–373	2.45–19.6	0.80–9.51	6.95
Kiyama and Makita (1956) [160]	24	298–373	0.1–78.5	0.03–22.2	4.52
Lavushchev and Lyusternik (1976) [166]	73	400–1990	0.1	Dilute Gas	0.35
Maitland and Smith (1972) [177]	22	80–1300	0.03–0.1	Dilute Gas	0.65
Makita (1955) [182]	30	298–473	0.1–10.1	0.02–4.3	3.63
Matthews et al. (1976) [185]	15	120–1700	0.1	Dilute Gas	0.48
Prosad (1952) [208]	15	91.2–93.6	0.11–0.14	35.1–35.5	3.91
Raw and Ellis (1958) [210]	11	769–1290	0.1	Dilute Gas	2.33
Rudenko and Schubnikow (1934) [221]	16	54.4–90.1	0–0.1	35.7–40.8	4.81
Rudenko (1939) [222]	8	77.4–154	0.02–4.97	16.5–37.6	23.3
Saji and Okuda (1965) [224]	5	80.1–87.5	0.03–0.07	36.1–37.2	3.68
Timrot et al. (1974) [253]	46	296–566	0.1–11.8	0.02–4.97	12.9
Trautz and Melster (1930) [256]	4	292–550	0.1	Dilute Gas	0.87
Trautz and Heberling (1931) [257]	9	294–523	0.1	Dilute Gas	0.67
Trautz and Zink (1930) [258]	12	556–1100	0.1	Dilute Gas	3.09
van Itterbeek and Claes (1936) [266]	12	72–294	0.001–0.1	Dilute Gas	3.16
van Itterbeek et al. (1966) [267]	14	77.3–90.2	0.03–2.44	35.7–37.7	6.47
van Itterbeek et al. (1966) [268]	32	69.9–89.9	0.01–9.75	35.7–39.1	4.52
Wobser and Muller (1941) [283]	5	293–371	0.1	Dilute Gas	0.24
Yen (1919) [284]	20	296	0.1	Dilute Gas	0.08
Oxygen-thermal conductivity					
Borovik (1947) [41]	5	156	0.1–9.81	0.07–23.6	6.42
Dickins (1934) [64]	5	277–285	0.1	Dilute Gas	1.21

Table VI. *(Continued)*

Author	No. Points	Temperature range (K)	Pressure range (MPa)	Density range ($\mathrm{mol \cdot dm^{-3}}$)	AAD (%)
Franck (1951) [78]	14	93–676	0.009–0.03	Dilute Gas	2.56
Geier and Schafer (1961) [80]	12	273–1370	0.1	Dilute Gas	0.65
Gregory and Marshall (1928) [94]	80	286–299	0.01–0.11	Dilute Gas	1.91
Hammann (1938) [99]	7	66–82.1	0.1	36.9–39.2	16.4
Ivanova et al. (1967) [115]	88	84.2–341	5.88–49	2.14–38.5	3.62
Jain and Saxena (1977) [120]	13	400–1600	0.1	Dilute Gas	2.36
Johnston and Grilly (1946) [125]	18	86.5–376	0.001–0.1	Dilute Gas	2.38
Keyes (1955) [157]	7	85.7–273	0.1–1.06	0.04–36.4	1.22
Nothdurft (1937) [202]	22	275–324	0.06–0.07	Dilute Gas	1.21
Pereira and Raw (1963) [205]	5	305–453	0.1	Dilute Gas	0.72
Prosad (1952) [208]	15	91.2–93.6	0.11–0.14	35.1–35.5	29.2
Roder (1982) [216]	1136	76.7–313	0.02–68.4	0.03–40.3	0.95
Saxena and Gupta (1970) [226]	13	350–1500	0.1	Dilute Gas	2.88
Tsederberg and Timrot (1957) [259]	78	73.2–313	0.01–10.1	0.01–38.7	2.11
Vanicheva et al. (1985) [269]	19	303–950	0.1	Dilute Gas	0.54
Weber (1982) [279]	76	153–174	4.72–8.74	11.7–18.8	33.8
Westenberg and deHaas (1963) [281]	10	300–1200	0.1	Dilute Gas	0.93
Yorizane et al. (1983) [285]	36	299–323	0.1–15	0.03–6.41	1.64
Zheng et al. (1984) [287]	20	298	0.1–17.8	0.04–7.59	1.18
Ziebland and Burton (1955) [288]	65	79.2–200	0.1–13.8	0.06–37.7	2.27
		Air-viscosity			
Bearden (1939) [37]	11	293	0.1	Dilute Gas	0.07
Braune et al. (1928) [45]	25	292–944	0.1	Dilute Gas	0.64
Carmichael and Sage (1966) [47]	6	294–378	0.1	Dilute Gas	0.54
Diller et al. (1991) [4]	64	70–130	3.43–32.2	16.5–33.1	0.88
Filippova and Ishkin (1959) [73]	32	90.2–273	0.09–14.7	0.04–29.8	7.54
Filippova and Ishkin (1962) [74]	53	90.2–273	1.99–14.8	0.88–29.6	14.1
Glassman and Bonilla (1953) [82]	24	200–2500	0.1	Dilute Gas	4.50
Golubev (1938) [87]	32	273–373	0.09–29.4	0.03–11.9	2.06
Golubev et al. (1971) [88]	105	293–776	2.03–50.7	0.31–15.6	2.00
Golubev (1970) [89]	53	273–373	0.1–30.4	0.03–12.2	0.72
Goring and Eagan (1971) [90]	12	423	3.62–10.8	1.02–2.95	2.49
Hellemans et al. (1973) [107]	19	298–873	0.1	Dilute Gas	0.33
Iwasaki and Kestin (1963) [116]	27	293	0.1	Dilute Gas	0.05
Iwasaki (1951) [118]	28	323–423	2.2–19.9	0.62–6.98	1.43
Johnston and McCloskey (1940) [127]	40	90.2–300	0.1	Dilute Gas	0.25
Johnston et al. (1951) [128]	16	80.3–306	0.001–0.09	Dilute Gas	0.60
Kellstroem (1941) [133]	73	293	0.77–3.09	0.31–1.28	0.12
Kestin and Wang (1958) [135]	13	298	0.1–10.1	0.04–4.12	0.39
Kestin and Whitelaw (1964) [137]	42	298–524	0.1–14.4	0.02–5.69	0.47
Kestin and Leidenfrost (1959) [141]	18	293–298	0.01–7	0.005–2.85	0.12
Kestin and Leidenfrost (1959) [142]	9	292–295	0.1–10.4	0.04–4.32	0.23
Kompaneets (1953) [162]	10	285–1070	0.1	Dilute Gas	2.65

Table VI. *(Continued)*

Author	No. Points	Temperature range (K)	Pressure range (MPa)	Density range $(\mathrm{mol \cdot dm^{-3}})$	AAD (%)
Kurin and Golubev (1974) [163]	36	293–323	9.81–325	3.63–30.5	1.55
Latto and Saunders (1973) [164]	26	101–398	0.11–14.5	0.03–13.5	1.14
Ling and Van Winkle (1958) [174]	4	273–464	0.1	Dilute Gas	0.59
Maitland and Smith (1972) [177]	16	80–700	0.0	Dilute Gas	0.38
Makita (1957) [181]	102	298–473	0.1–81.1	0.02–19.5	2.54
Matthews et al. (1976) [185]	15	120–1700	0.1	Dilute Gas	0.41
Moulton and Beuschlein (1940) [197]	45	303	0.92–30.3	0.36–10.8	9.03
Nasini and Pastonesi (1933) [199]	18	287	0.1–20.3	0.04–8.31	3.89
Rudenko (1939) [222]	5	90.1–126	0.3–2.92	19.1–28.4	33.5
Sutherland and Maass (1932) [246]	7	79–294	0.1	0.04–4.08	5.38
Timrot et al. (1974) [253]	46	296–566	0.1–11.8	0.02–4.73	0.43
Timrot et al. (1975) [254]	46	296–566	0.0	Dilute Gas	2.96
Trautz and Zink (1930) [258]	94	346–1100	0.1	Dilute Gas	5.52
Van Dyke (1923) [265]	5	296	0.09	Dilute Gas	0.70
Wobser and Muller (1941) [283]	5	293–371	0.0	Dilute Gas	0.35
Air-thermal conductivity					
Amirkhanov and Adamov (1963) [28]	5	293–313	0.1	Dilute Gas	1.39
Carmichael and Sage (1966) [47]	6	294–378	0.1	Dilute Gas	0.40
Carroll et al. (1968) [48]	378	160–800	0.1–101	0.01–28.8	2.43
Fleeter et al. (1980) [75]	33	300–301	0.81–36.2	0.32–12.4	0.25
Gambhir et al. (1967) [79]	4	308–363	0.1	Dilute Gas	0.61
Geier and Schafer (1961) [80]	12	273–1370	0.1	Dilute Gas	2.66
Glassman and Bonilla (1953) [82]	24	200–2500	0.1	Dilute Gas	4.58
Golubev (1963) [86]	72	196–426	0.1–50.7	0.02–22	2.98
Irving et al. (1973) [114]	4	273–448	0.1	Dilute Gas	2.58
Kannuluik and Carman (1951) [130]	46	90.2–491	0.002–0.1	Dilute Gas	1.85
Kannuluik and Martin (1934) [131]	8	276	0.001–0.1	Dilute Gas	0.64
Mustafaev (1972) [198]	14	423–677	0.1	Dilute Gas	0.47
Perez Masia and Roig (1958) [206]	7	277–406	0.0	Dilute Gas	2.16
Perkins and Cieszkiewicz (1991) [10]	1066	70–304	0.15–70.2	0.20–34.1	0.45
Roder (1966) [217]	27	60–110	0.001–0.5	0.002–0.69	1.28
Saksena and Saxena (1966) [225]	6	313–413	0.1	Dilute Gas	2.52
Schluender (1964) [230]	6	293–699	0.1	Dilute Gas	1.16
Scott et al. (1981) [234]	43	309–375	0.87–23.8	0.27–8.7	0.24
Senftleben (1963) [235]	8	273–673	0.1	Dilute Gas	1.68
Senftleben (1964) [236]	8	273–673	0.1	Dilute Gas	1.69
Stolyarov et al. (1950) [243]	16	274–673	1.08–19.5	0.19–8.54	5.08
Tarzimanov and Salmanov (1977) [247]	40	406–1200	0.1–100	0.01–13.4	1.69
Tarzimanov and Lozovoi (1968) [249]	66	299–794	0.1–99.1	0.01–20.1	1.26
Taylor and Johnston (1946) [250]	43	87.5–376	0.001–0.02	Dilute Gas	2.26
Tsederberg and Ivanova (1971) [260]	85	82.6–368	9.81–49	3.14–32.7	4.41
Vargaftik and Oleshchuk (1946) [272]	12	317–1070	0.1	Dilute Gas	3.30
Vines (1960) [276]	4	513–1170	0.1	Dilute Gas	0.57

fewer data points were generally excluded from this list. The average absolute deviations are based on the percent deviation in any property, X, defined as

$$\%\Delta X = 100\left(\frac{X_{\text{data}} - X_{\text{calc}}}{X_{\text{data}}}\right). \tag{12}$$

Figures 1 through 16 compare calculated values from the equations to the experimental data. Smaller datasets were excluded from some of the comparisons to eliminate crowding in both graphs and legends. In these figures, data are separated into temperature increments of 10 K or more; the temperatures listed at the top of each small plot are the lower bounds of the data in the plot. The discussion of deviations in the following text generally focuses on the average absolute deviation of calculated values from various datasets, and points with large apparent errors in a particular dataset are not considered when discussing deviation ranges and scatter.

Figures 1 through 4 and 9 through 12 compare the transport property formulations developed in this work to the dilute gas data. Only experimental data in the vapor phase at pressures less than 1 MPa were included in these figures. Thus, the calculations are a composite of the dilute gas equations given in Eqs. (2) and (5) and a small contribution from the residual fluid behavior given in Eqs. (3) and (6). The major portion of each calculated property comes from the dilute gas equations. The ranges for deviations on the plots span from −5 to 5%, except those for the viscosity of nitrogen and argon (which span from −2 to 2%).

As shown in Figs. 1 through 4, the dilute gas experimental data for viscosity are generally represented to within 0.5% for nitrogen and argon, and within 1% for oxygen and air. In Fig. 3 there are two datasets for oxygen, van Itterbeek and Claes [266] and Haynes [104], at temperatures below 200 K with deviations that exceed 1% and that disagree with the data of Johnston and McCloskey [127], Maitland and Smith [177], and Matthews et al. [185]. It is unclear which of these data give a better representation of the true properties of oxygen and uncertainty estimates must include all these data. At high temperatures for all four fluids there are two distinct groupings of data: one grouping was used to fit the equations; the second grouping of data shows systematic negative deviations from those selected for developing the equations reported here. For nitrogen, the trend starts at temperatures near 300 K, including the datasets of Bonilla et al. [38], Ellis and Raw [70], Rigby and Smith [214], and Trautz and Zink [258], and reaches a maximum deviation of −14% at 2500 K as shown in Fig. 17. Data for the other fluids show similar trends.

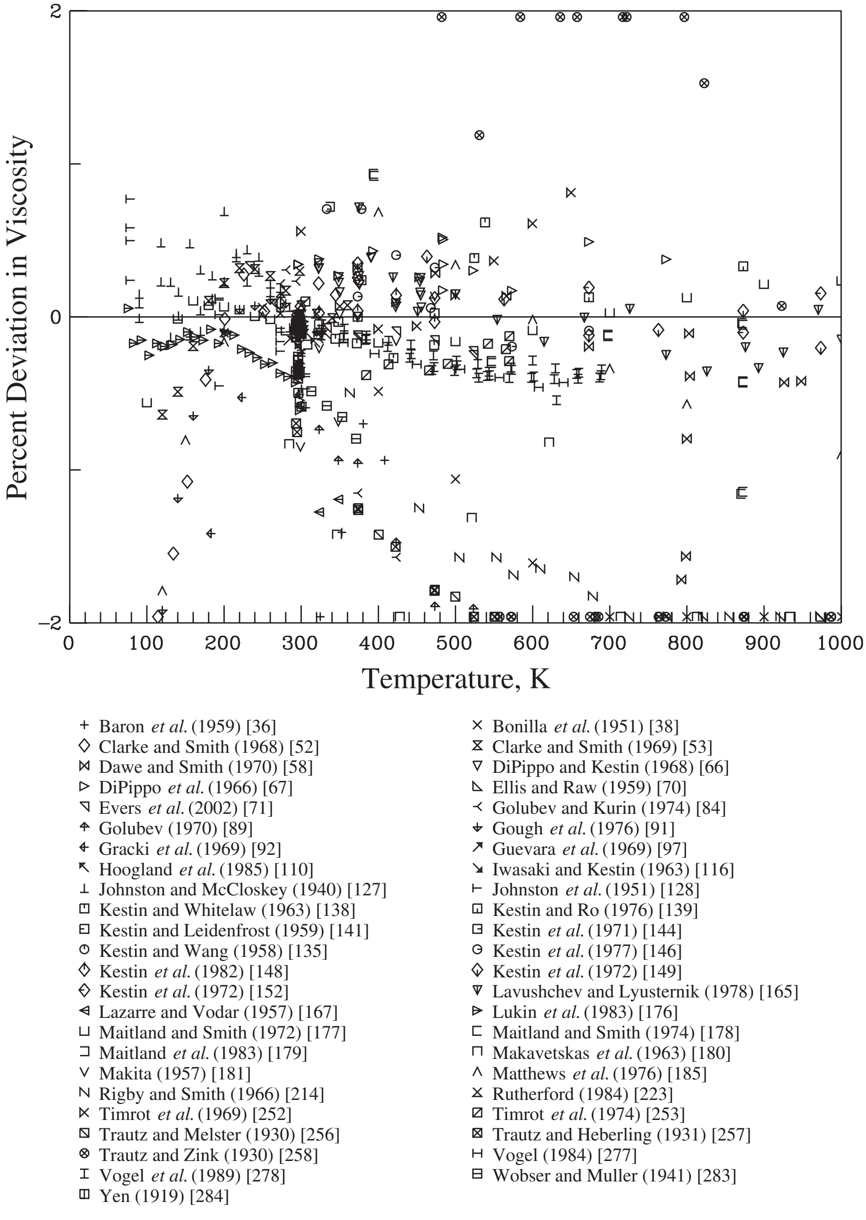

Fig. 1. Comparisons of calculated viscosities of nitrogen to experimental data in the dilute gas.

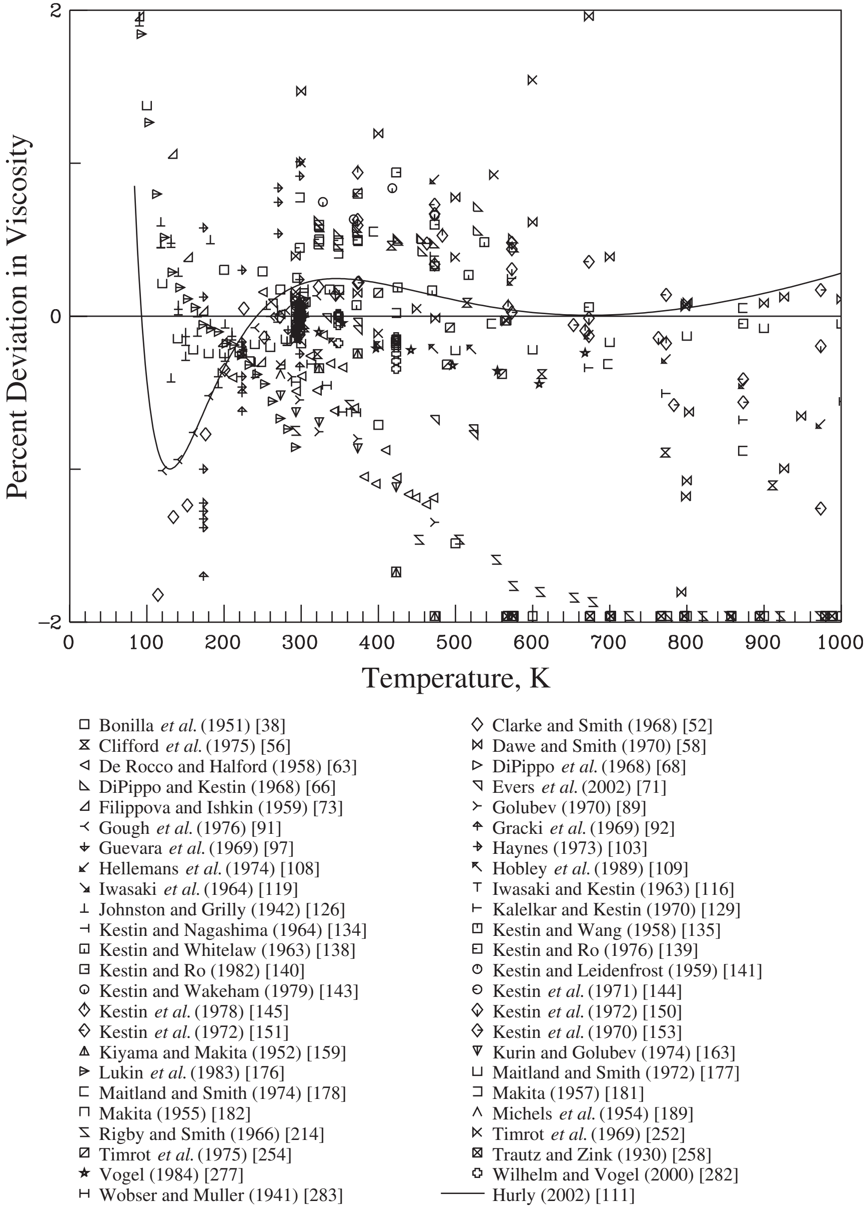

Fig. 2. Comparisons of calculated viscosities of argon to experimental data in the dilute gas.

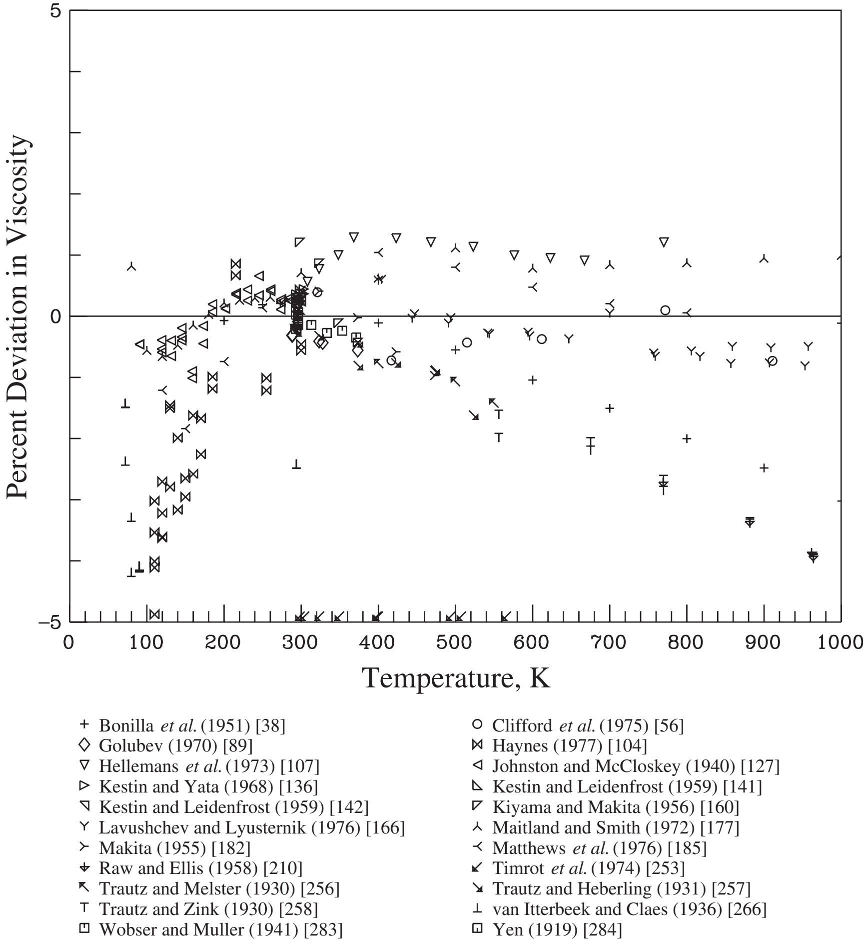

Fig. 3. Comparisons of calculated viscosities of oxygen to experimental data in the dilute gas.

Comparisons of the residual (or non-dilute) viscosity are shown in Figs. 5 through 8. The scatter in the data is considerably higher than that for the dilute gas. At temperatures below (and near) the critical point, the scatter can exceed 10%. The datasets containing the lowest temperatures with reliable data are:

- nitrogen: van Itterbeek et al. [268] at 70 K
- argon: Abachi et al. [27] at 84 K

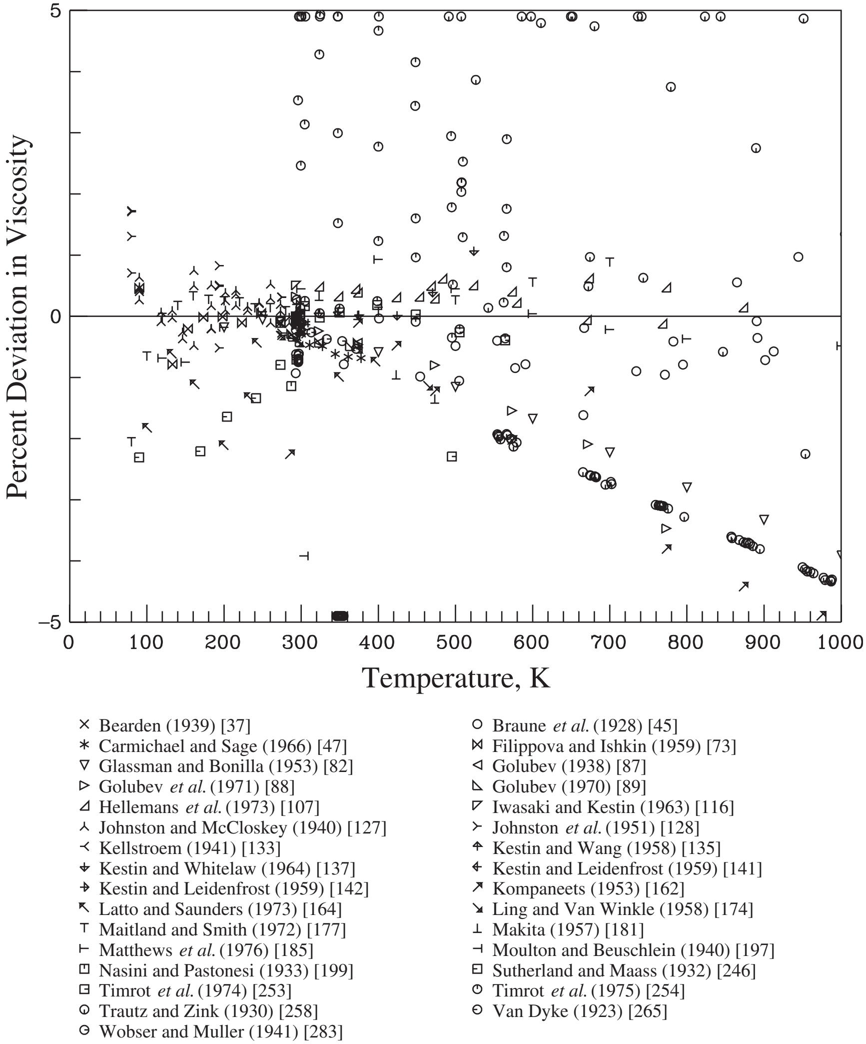

Fig. 4. Comparisons of calculated viscosities of air to experimental data in the dilute gas.

- oxygen: Rudenko [222] at 55 K
- air: Diller et al. [4] at 70 K.

Only data for argon and oxygen extend to the triple point, and the liquid phase data for oxygen are in poor agreement with each other, differing by more than 20% in the extreme cases. At nominal temperatures between 270 and 370 K, the scatter in the data sets is much smaller. For example, at

290 K for nitrogen and argon, the scatter is generally within 2% over all pressures up to 100 MPa. At higher pressures, the scatter increases up to 10%. Comparisons of calculated viscosities to data sets for nitrogen between 270 and 370 K show average absolute deviations of 0.078% for the data of Evers et al. [71], 0.10% for Kestin et al. [144], 0.12% for Hoogland et al. [110], 0.25% for Michels and Gibson [187], and 0.54% for Makita [181]. Deviations for argon between 270 and 370 K below 100 MPa are 0.09% for the data of Wilhelm and Vogel [282], 0.09% for Flynn et al. [76], 0.20% for Evers et al. [71], 0.20% for Michels et al. [189], and 0.27% for Kestin et al. [144]. Some of the data used in fitting included those of Evers et al. [71] and Diller [65] for nitrogen and Evers et al. [71], Haynes [103], and Wilhelm and Vogel [282] for argon. For oxygen between 270 and 370 K, the very limited data show deviations of 0.4% for Haynes [104] and 0.19% for Kestin and Yata [136] (both were used in fitting). For air in the same temperature range, deviations are 0.23% for the data of Timrot et al. [253] and 0.30% for Kestin and Whitelaw [137].

The scatter in the experimental data for the dilute gas thermal conductivity is much larger than that for the viscosity. Figures 9 through 12 show that the data are represented to within 2% but that there are several data points with deviations of 5% and greater. For argon between 290 and 350 K, where much of the dilute gas data reside, the deviations range from −2% to 1% (excluding points with excess deviations), even for datasets measured during the last 20 years. The correlation presented here was based partly on the work of Sun et al. [245] and on calculations from Hurly [111], which used the intermolecular potential of Aziz [33].

Comparisons of the residual fluid behavior for thermal conductivity are shown in Figs. 13 through 16. The datasets containing the lowest temperatures with reliable data are:

- nitrogen: Perkins et al. [6] at 81 K
- argon: Ziebland and Burton [289] at 93 K
- oxygen: Tsederberg and Timrot [259] at 73 K
- air: Perkins and Cieszkiewicz [10] at 70 K.

There are no reliable data located near the triple points of any of the fluids. At nominal temperatures between 270 and 370 K, the scatter in the data sets is generally 4%. Comparisons of values calculated using the thermal conductivity equation to some data sets for nitrogen show average absolute deviations of 0.31% for Assael and Wakeham [31], 0.40% for the data of Clifford et al. [54], 0.40% for Haran et al. [102], 0.85% for Perkins et al. [6], 1.0% for Roder [215], and 1.2% for Mostert et al. [194]. Similar

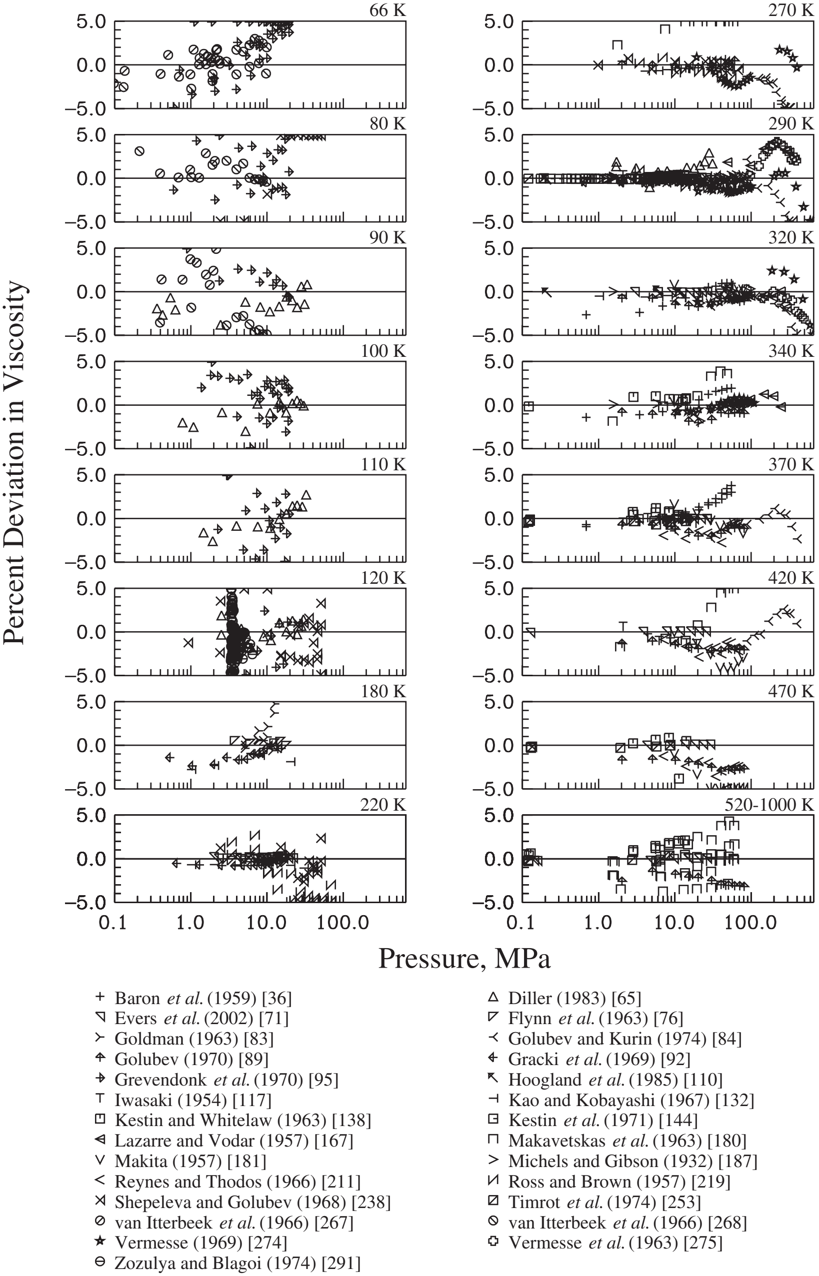

Fig. 5. Comparisons of calculated viscosities of nitrogen to experimental data in vapor and liquid states.

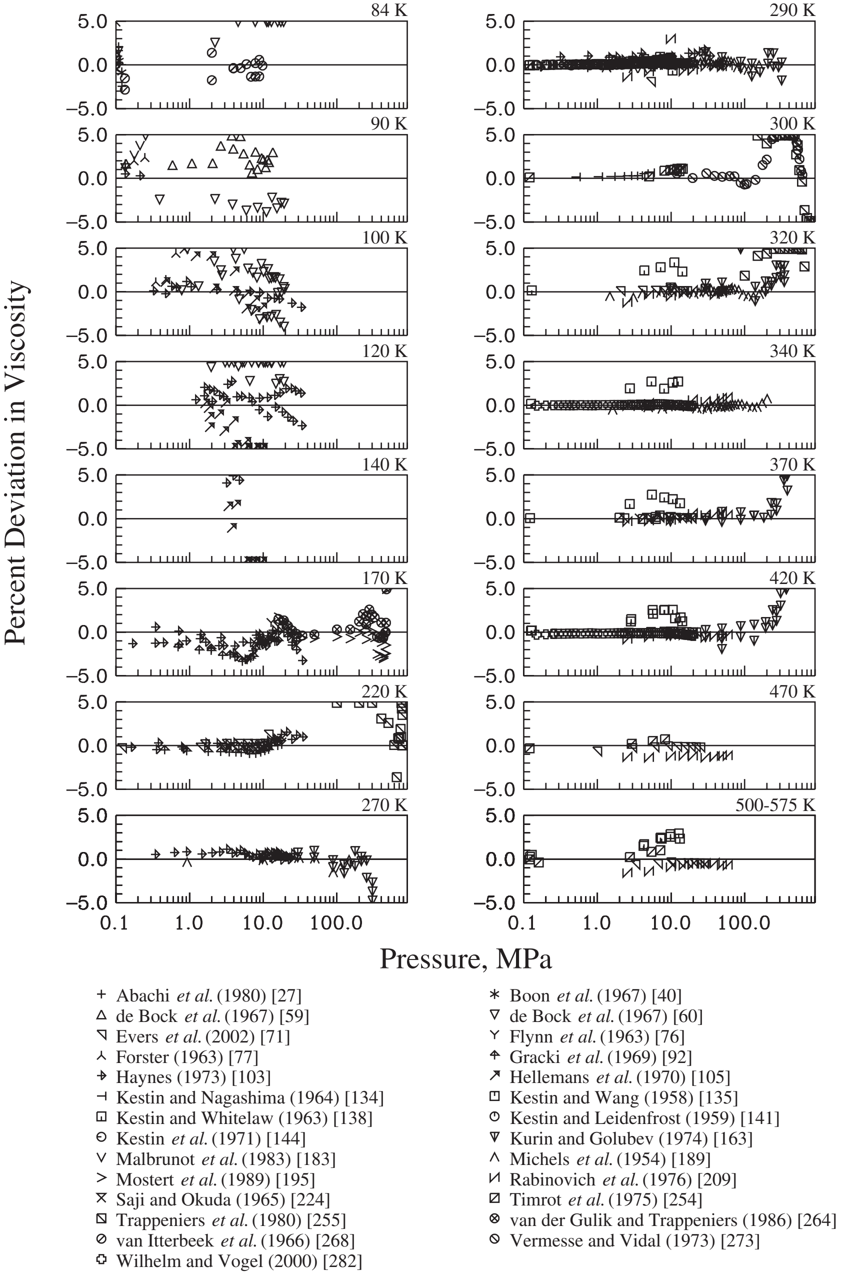

Fig. 6. Comparisons of calculated viscosities of argon to experimental data in vapor and liquid states.

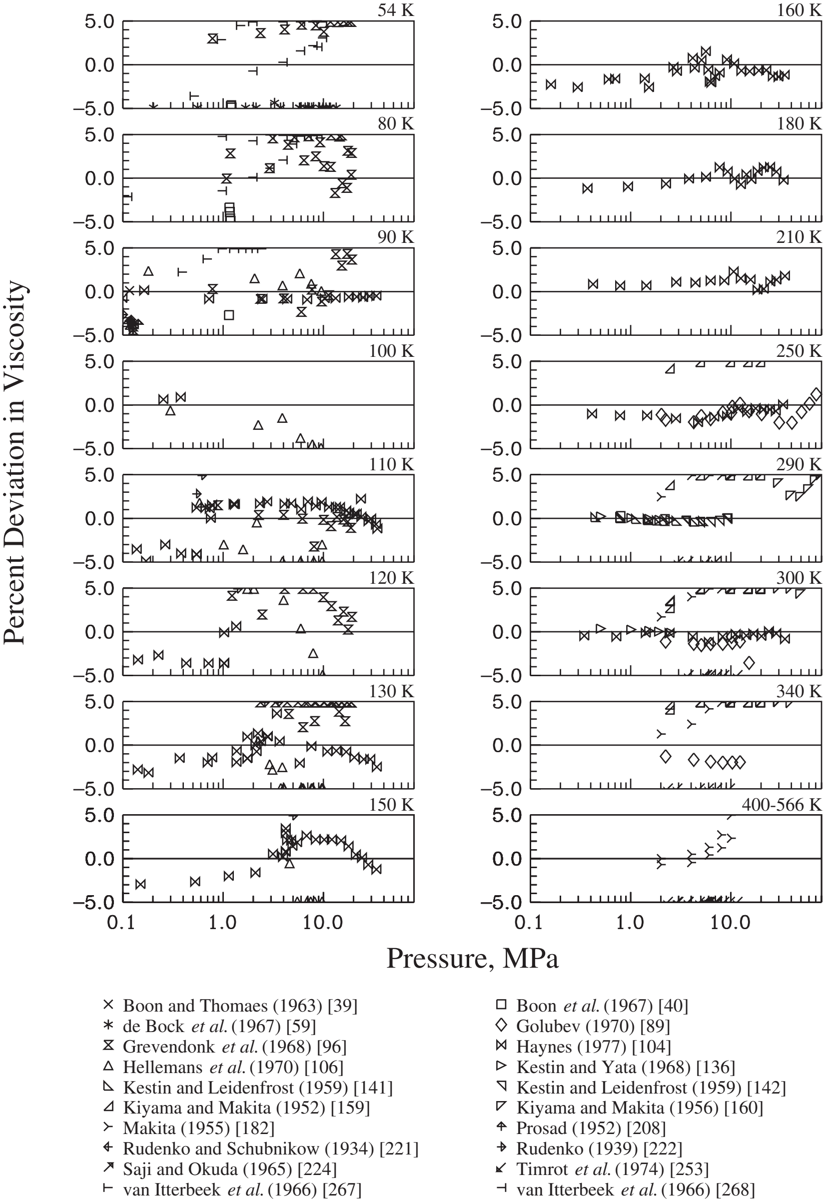

Fig. 7. Comparisons of calculated viscosities of oxygen to experimental data in vapor and liquid states.

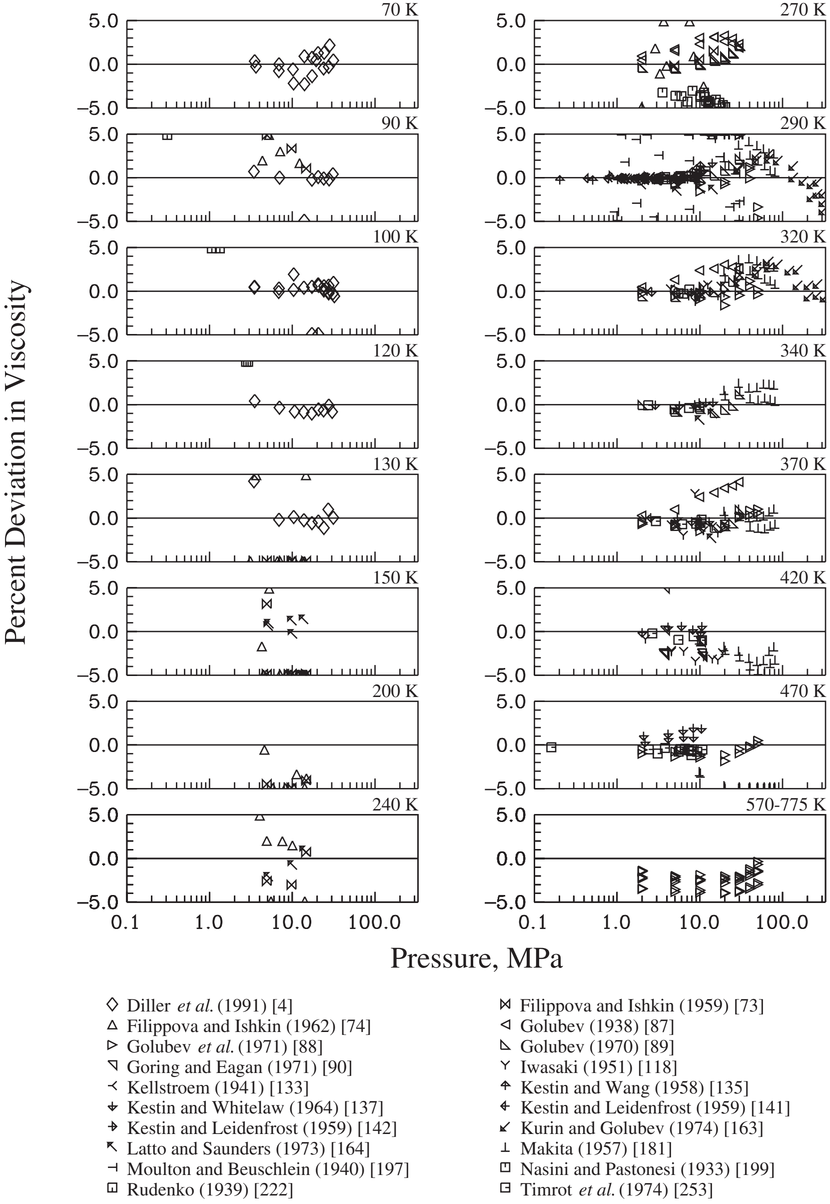

Fig. 8. Comparisons of calculated viscosities of air to experimental data in vapor and liquid states.

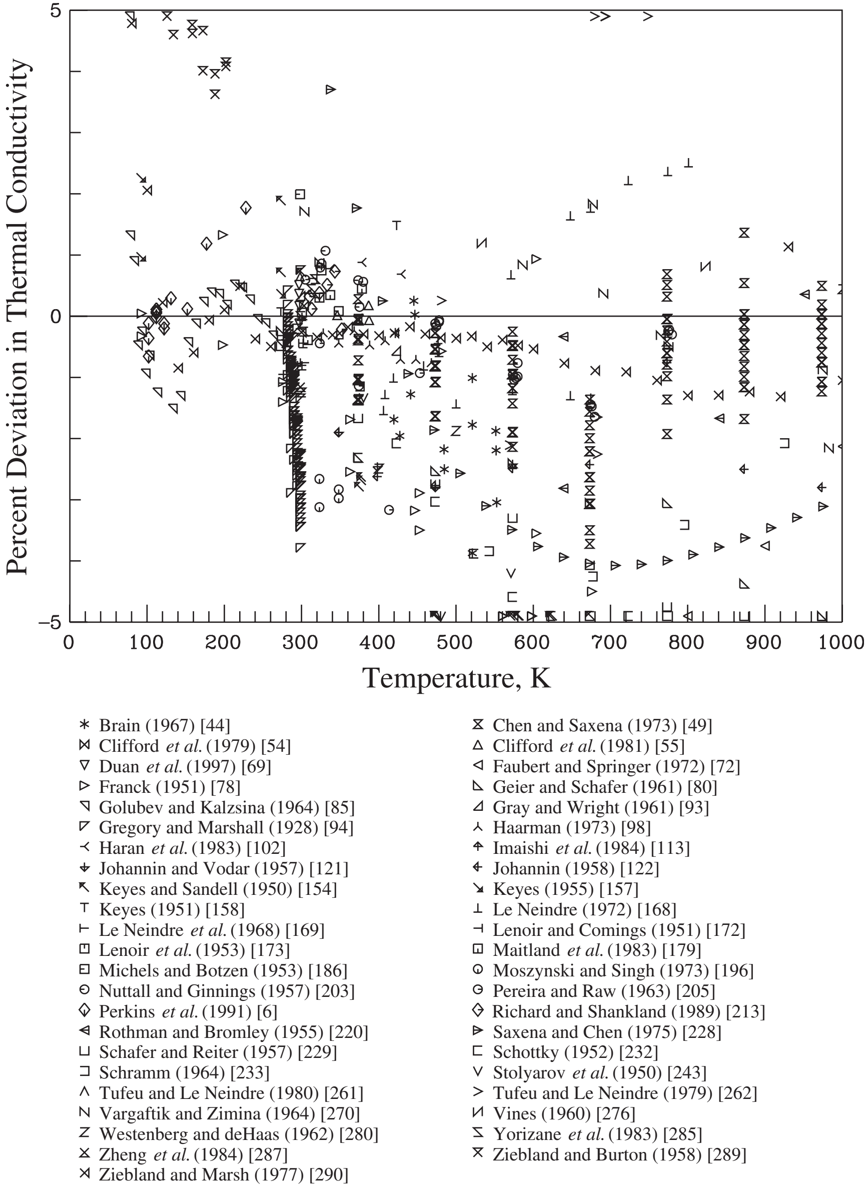

Fig. 9. Comparisons of calculated thermal conductivities of nitrogen to experimental data in the dilute gas.

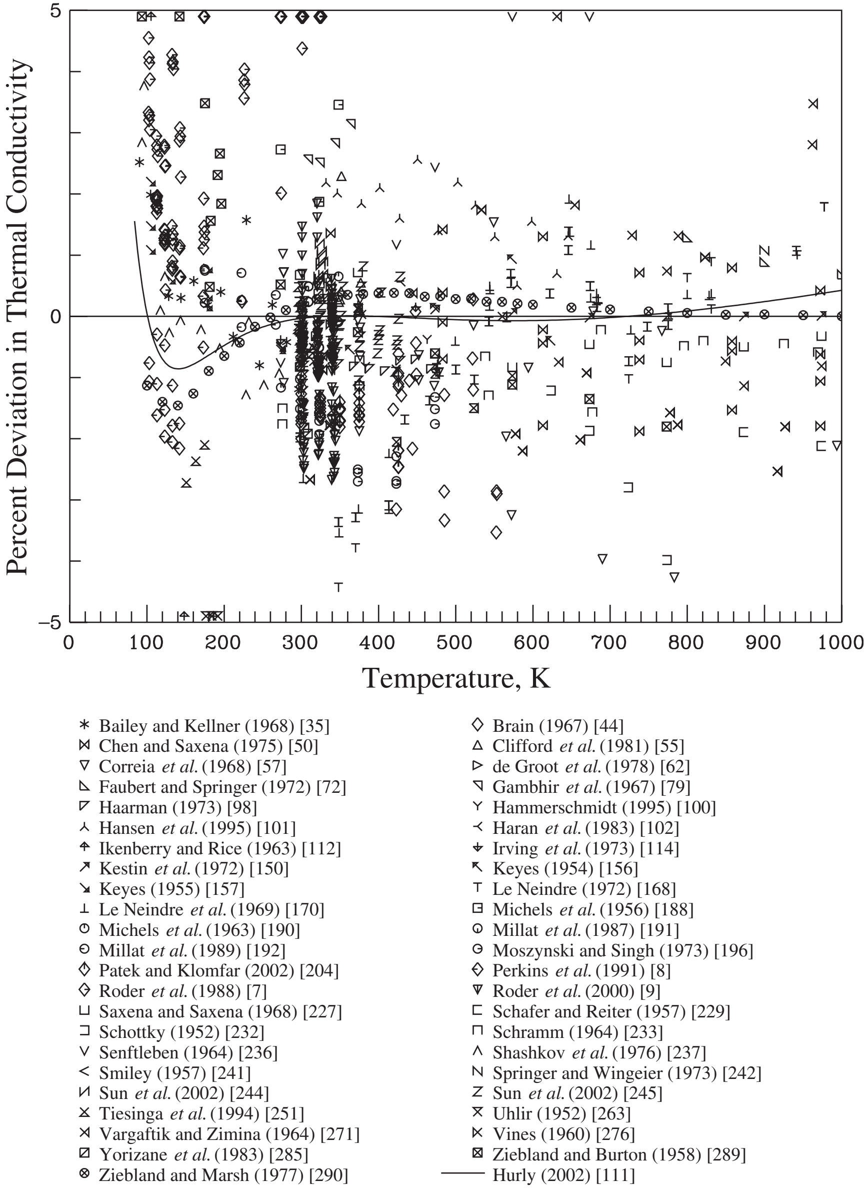

Fig. 10. Comparisons of calculated thermal conductivities of argon to experimental data in the dilute gas.

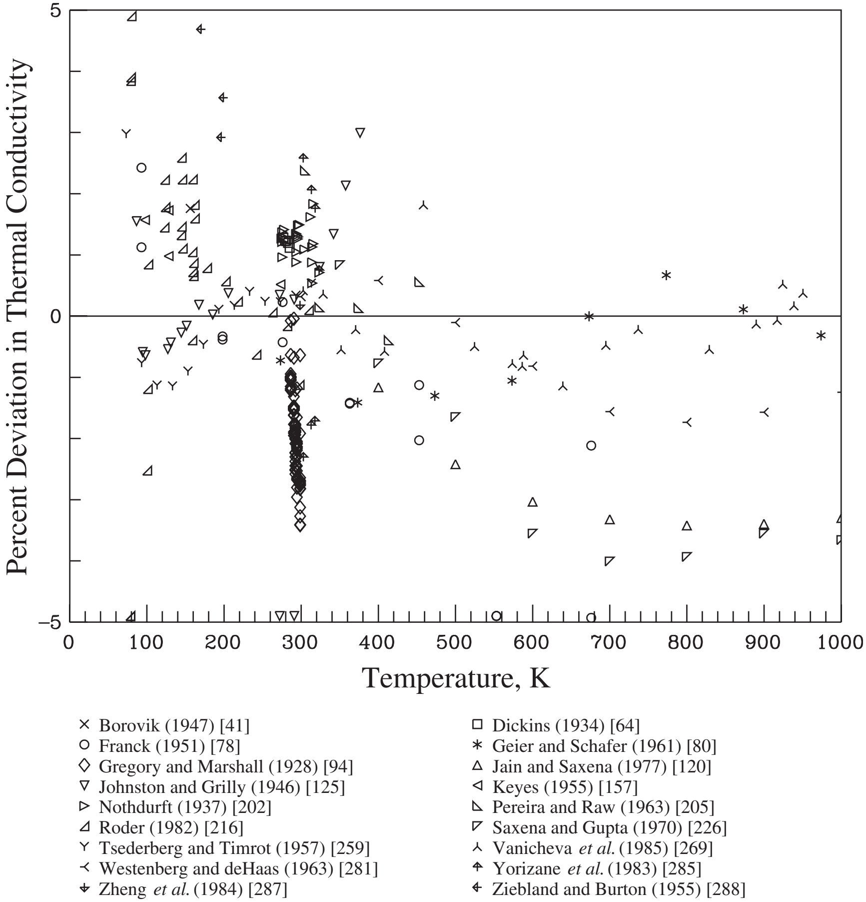

Fig. 11. Comparisons of calculated thermal conductivities of oxygen to experimental data in the dilute gas.

deviations for argon between 270 and 370 K below 100 MPa are 0.24% for the data of Sun et al. [245], 0.32% for Assael et al. [32], 0.37% for Clifford et al. [55], 0.48% for Perkins et al. [8], 0.80% for Roder et al. [9], and 1.0% for Patek and Klomfar [204]. For oxygen between 270 and 370 K, deviations are 0.8% for the data of Roder [216], and the deviations for air are 0.6% for the data of Perkins and Cieszkiewicz [10]. The data used in fitting equations for these fluids included those of Perkins et al. [6, 10], Mardolcar et al. [184], and Roder et al. [7, 216].

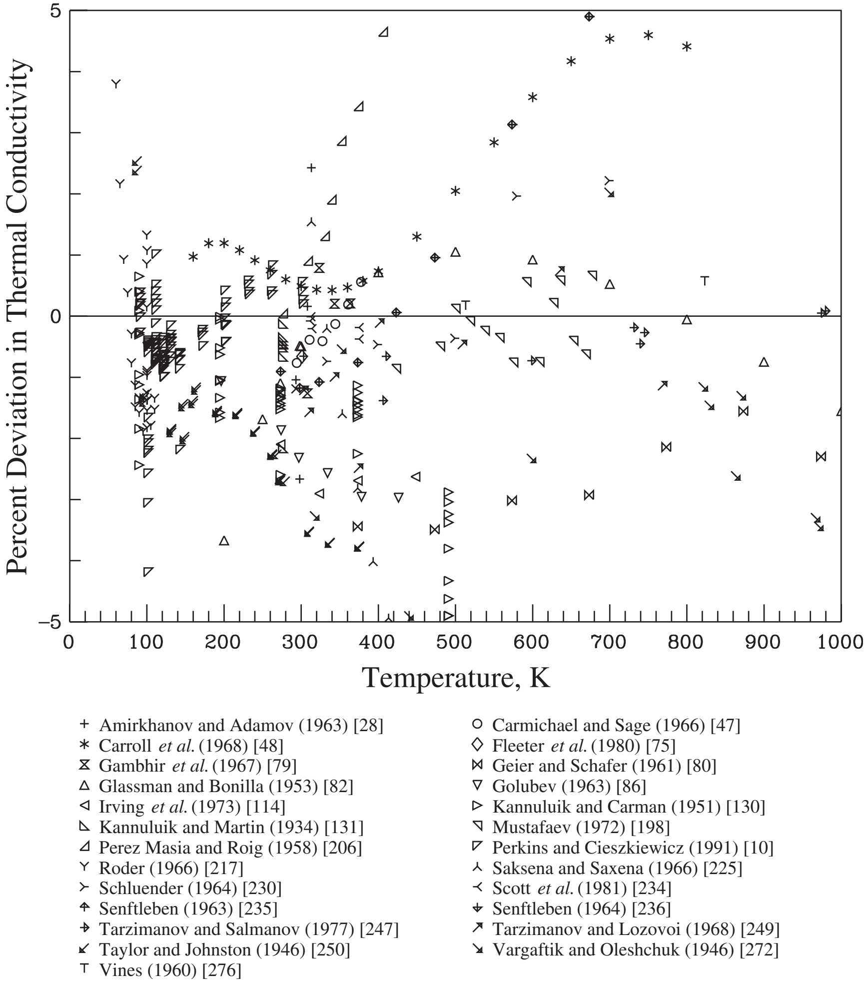

Fig. 12. Comparisons of calculated thermal conductivities of air to experimental data in the dilute gas.

4. EXTRAPOLATION BEHAVIOR

The equations for argon and nitrogen were developed to ensure that extrapolated properties below the triple point and at high temperatures and pressures would be reasonable so that the equations could be used in corresponding states applications. Negative exponents on temperature were not allowed in the residual part of the equations so that the contributions at high temperatures would go to zero. At low temperatures in both the

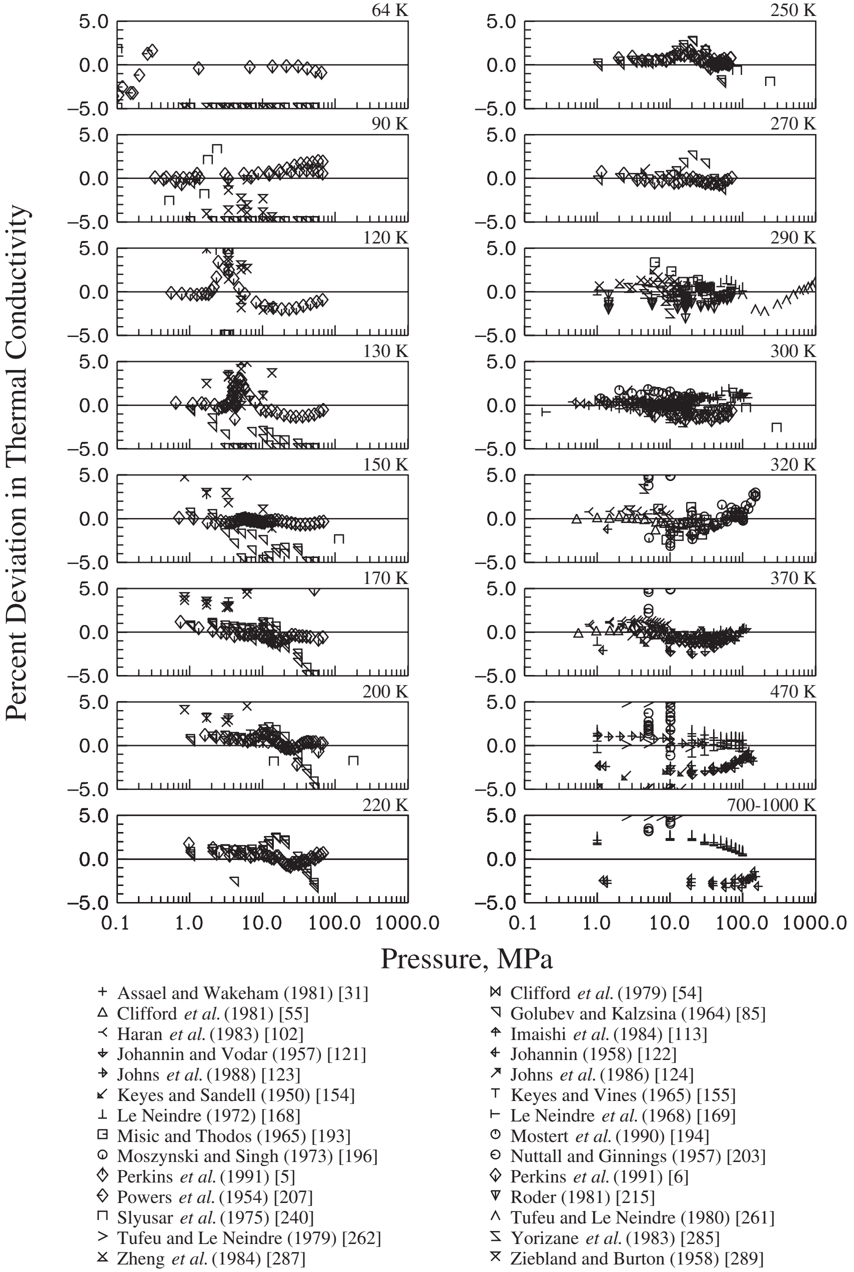

Fig. 13. Comparisons of calculated thermal conductivities of nitrogen to experimental data in vapor and liquid states.

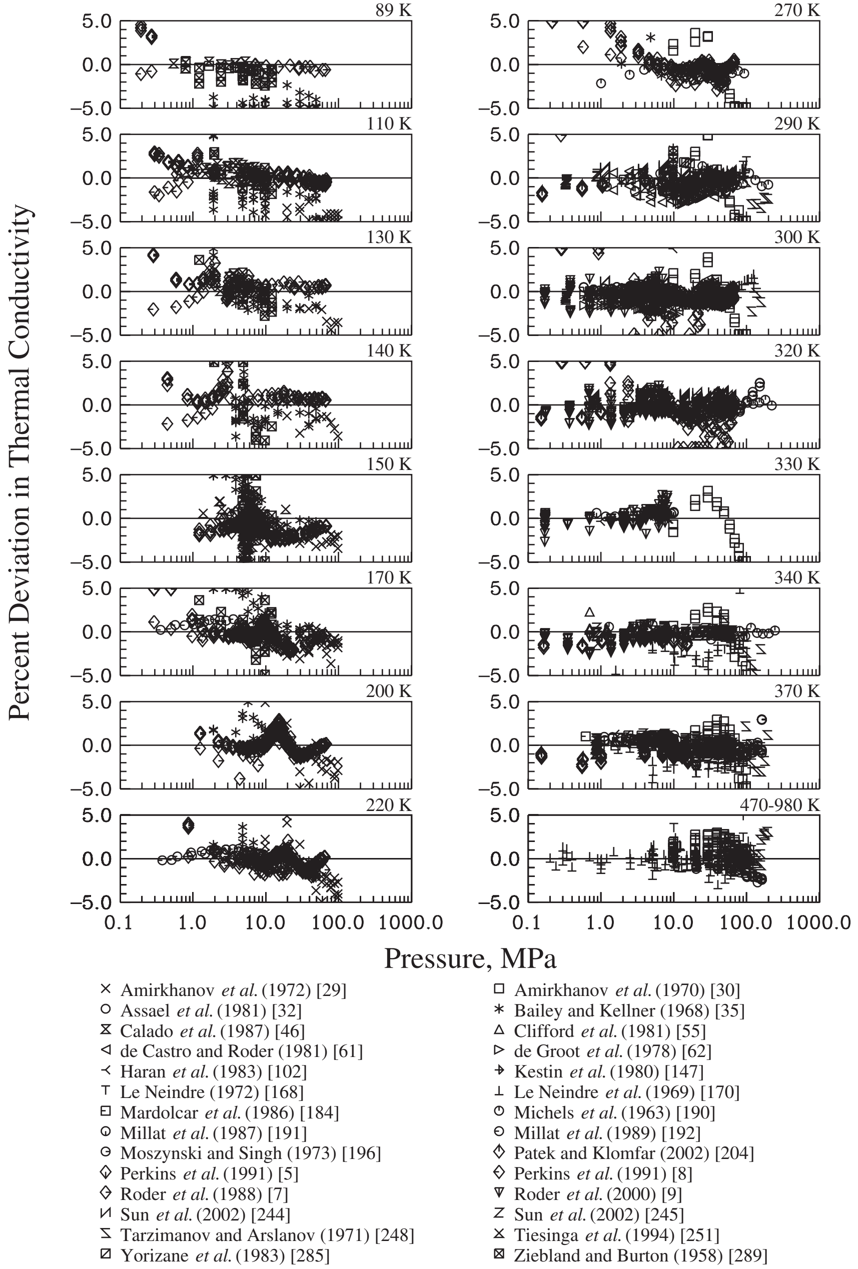

Fig. 14. Comparisons of calculated thermal conductivities of argon to experimental data in vapor and liquid states.

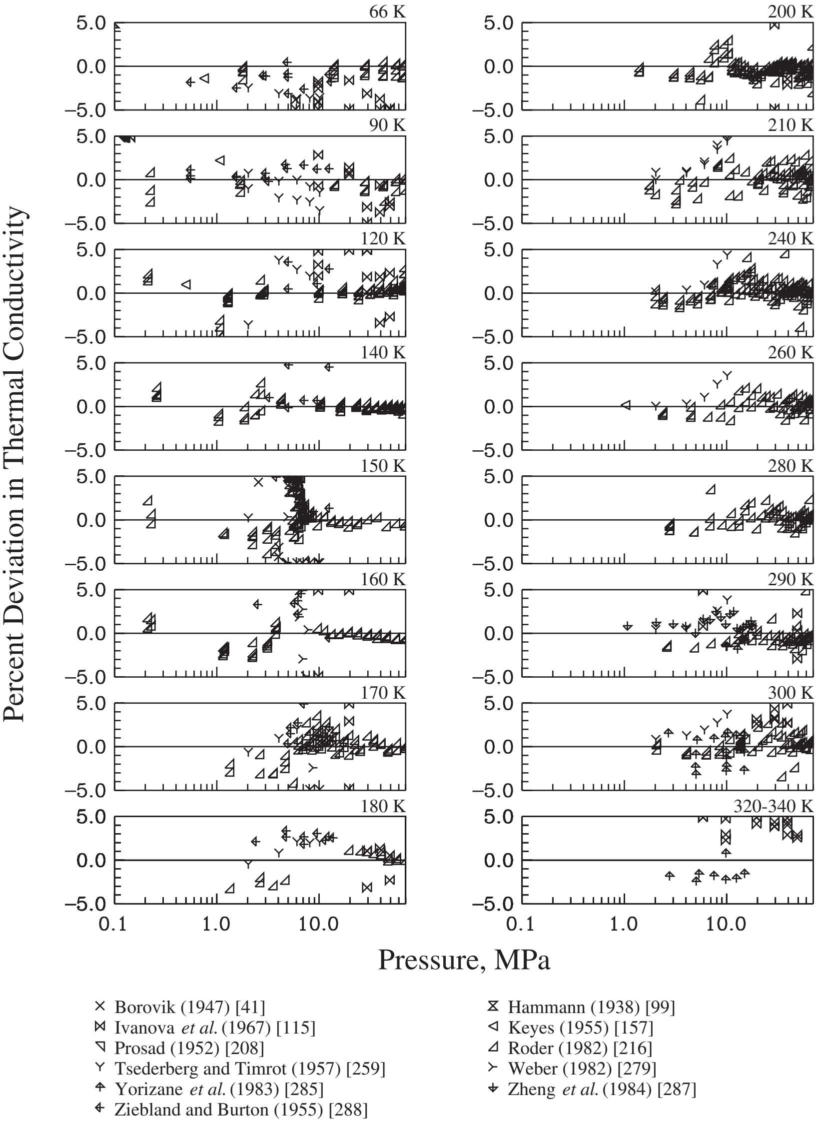

Fig. 15. Comparisons of calculated thermal conductivities of oxygen to experimental data in vapor and liquid states.

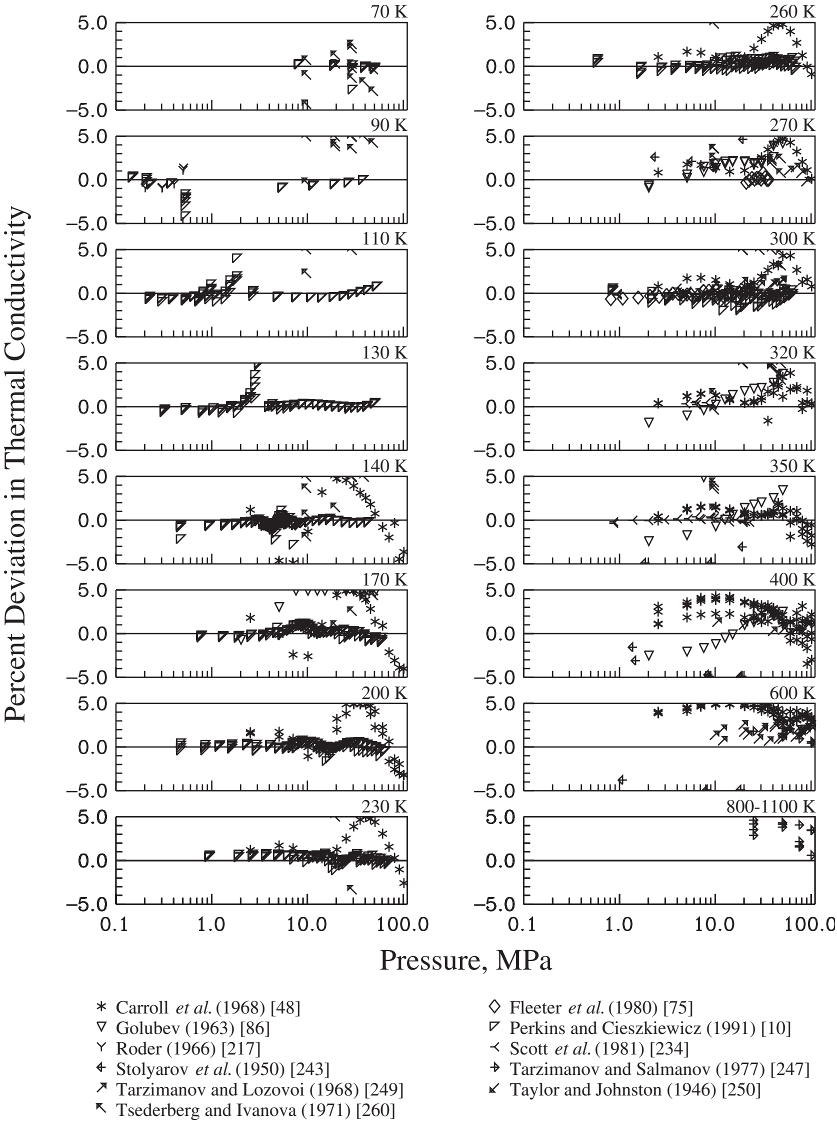

Fig. 16. Comparisons of calculated thermal conductivities of air to experimental data in vapor and liquid states.

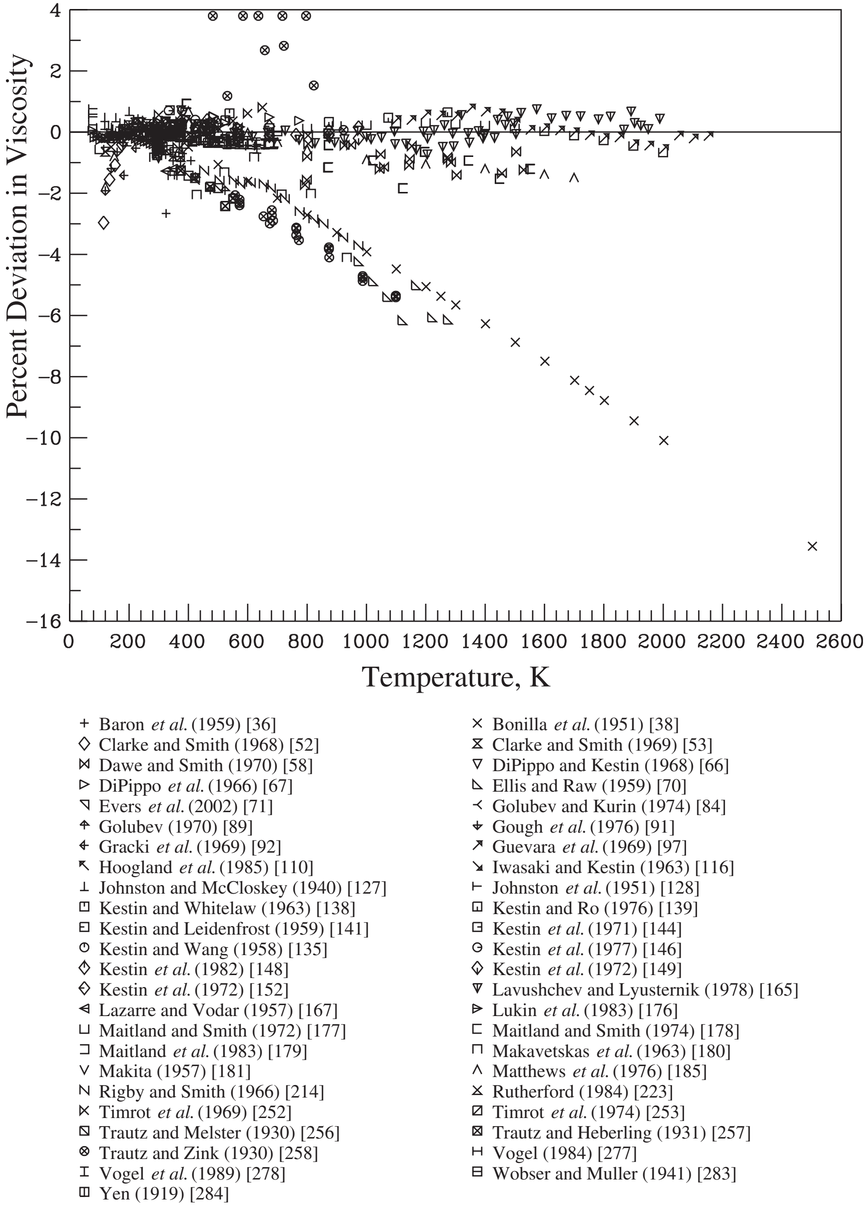

Fig. 17. Comparisons of calculated viscosities of nitrogen to experimental data in the dilute gas including states at high temperatures.

liquid and vapor phases, graphical comparisons were used to obtain reasonable shapes of the isobars and isotherms. The equations of state for the thermodynamic properties must also extrapolate well to low temperatures to ensure reasonable values of extrapolated transport properties. This is the case for both nitrogen and argon. Figures 18 and 19 show the viscosities of nitrogen and argon at temperatures well below their triple points. The properties are well behaved down to about 20 K for nitrogen and to about 50 K for argon. These limits represent reduced temperatures of 0.16 for nitrogen and 0.33 for argon. Figures 20 and 21 show the viscosities of nitrogen and argon as functions of density, rather than temperature. The solid lines are isobars, and saturation properties are shown with dashed lines. The isobars in these figures differ from those shown in Figs. 18 and 19 in that the viscosity is calculated through the two-phase region as a function of density and temperature without recognizing the saturation boundaries. In Figs. 18 and 19, the saturation boundaries were simply connected with straight lines. Thus, Figs. 20 and 21 show that there is no objectionable behavior of the equations within the two-phase region, something not typical of equations of state for the thermodynamic properties (see Lemmon and Jacobsen [292]). The figures also show that the extrapolation up to 50 $\mathrm{mol \cdot dm^{-3}}$ is reasonable, well beyond the saturated liquid density at the triple point.

Figures 22 through 25 show similar plots for the thermal conductivity. The critical enhancement contribution has been removed from calculated values shown in Figs. 24 and 25 to allow examination of the residual contributions. The only obviously incorrect physical behavior is that which occurs as slope reversals in the two-phase region as temperatures drop below 50 K for both fluids (well below their triple point temperatures). These "bumps" are well away from the saturation boundaries, which is important in mixture modeling where calculated values within the two-phase region are often used.

5. ESTIMATED UNCERTAINTIES OF CALCULATED PROPERTIES

Overall, the uncertainties of calculated values from the transport equations are generally within 2% for nitrogen and argon and within 5% for oxygen and air, except in the critical region where the uncertainties are higher. For the air mixture, the transport equations should not be used to calculate values in the close vicinity of the critical and maxcondentherm points. On a more detailed basis, the uncertainties for viscosity are 0.5% in the dilute gas for nitrogen and argon, 1% in the dilute gas for air and for oxygen at temperatures above 200 K, and 5% in the dilute gas for oxygen at lower temperatures. Away from the dilute gas (pressures greater than

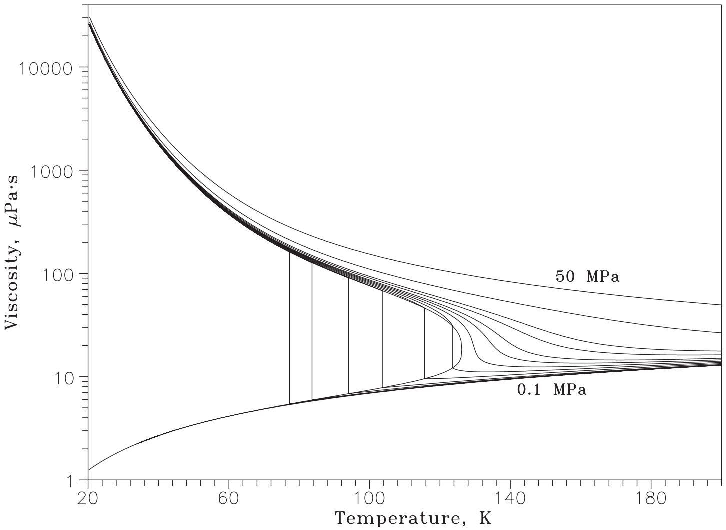

Fig. 18. Viscosity versus temperature diagram for nitrogen showing the isobars 0.1, 0.2, 0.5, 1, 2, 3, 4, 5, 6, 8, 10, 20, and 50 MPa.

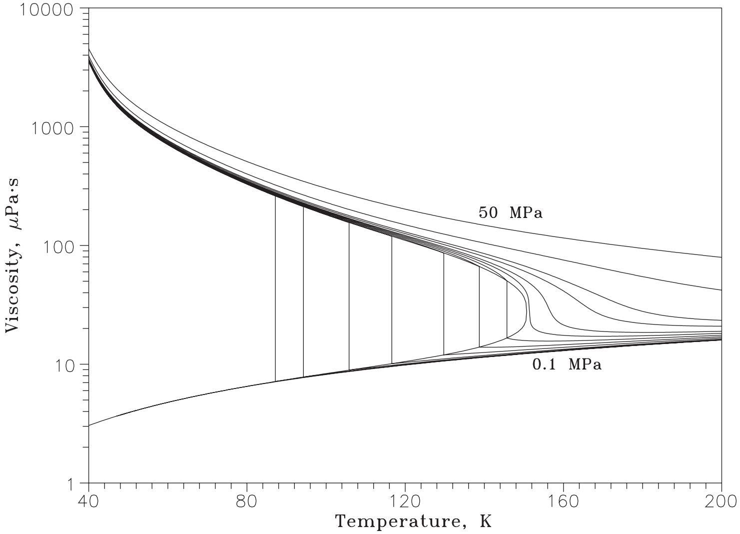

Fig. 19. Viscosity versus temperature diagram for argon showing the isobars 0.1, 0.2, 0.5, 1, 2, 3, 4, 5, 6, 8, 10, 20, and 50 MPa.

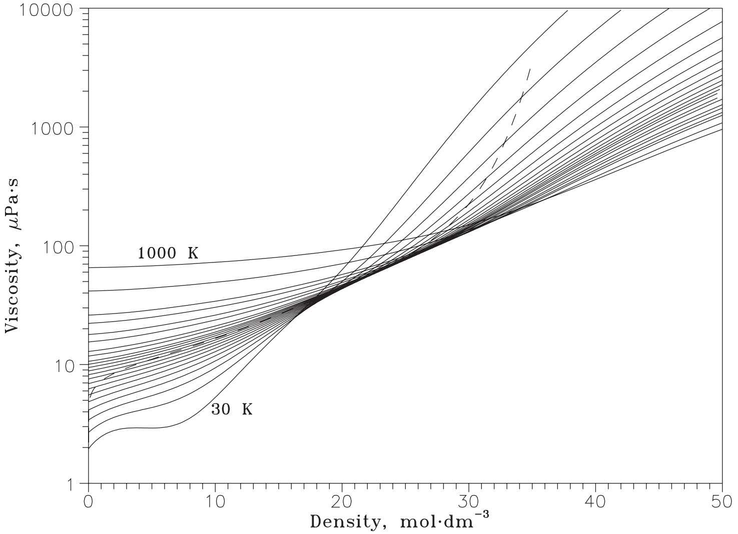

Fig. 20. Viscosity versus density diagram for nitrogen showing the isotherms 30 through 160 K at every 10 K, and 180, 200, 250, 300, 400, 500, and 1000 K.

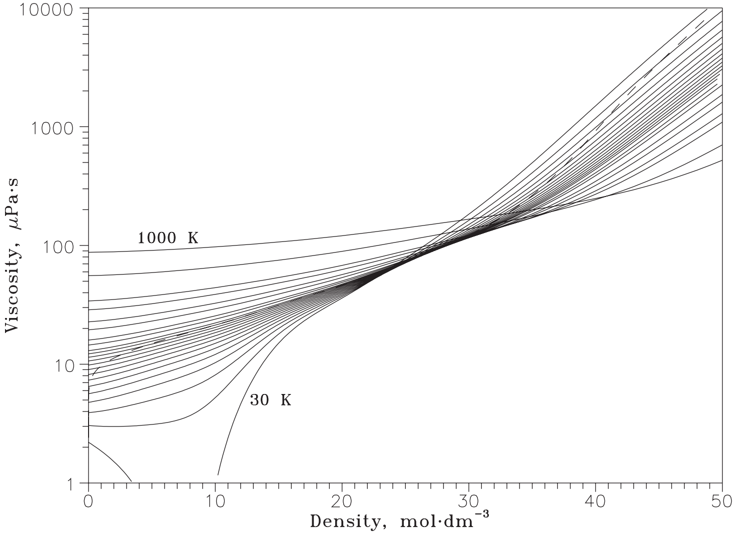

Fig. 21. Viscosity versus density diagram for argon showing the isotherms 30 through 160 K at every 10 K, and 180, 200, 250, 300, 400, 500, and 1000 K.

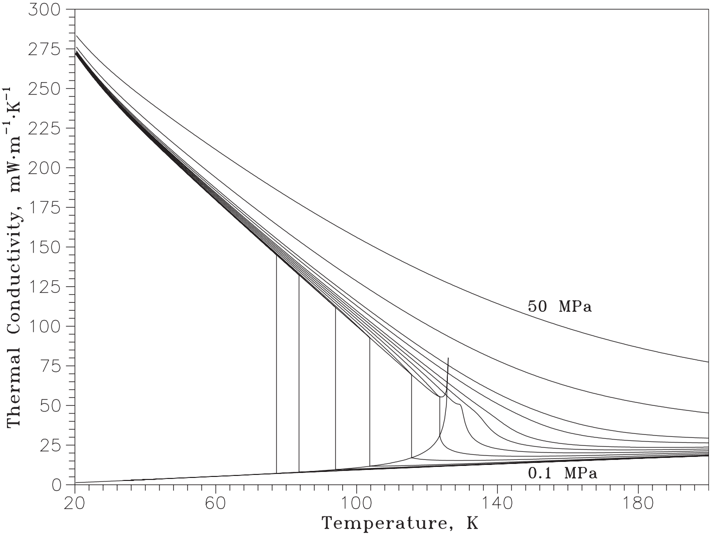

Fig. 22. Thermal conductivity versus temperature diagram for nitrogen showing the isobars 0.1, 0.2, 0.5, 1, 2, 3, 4, 5, 6, 8, 10, 20, and 50 MPa.

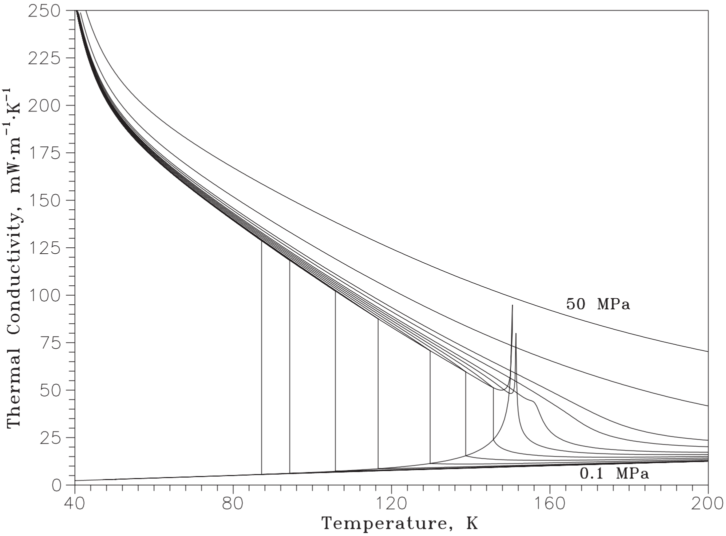

Fig. 23. Thermal conductivity versus temperature diagram for argon showing the isobars 0.1, 0.2, 0.5, 1, 2, 3, 4, 5, 6, 8, 10, 20, and 50 MPa.

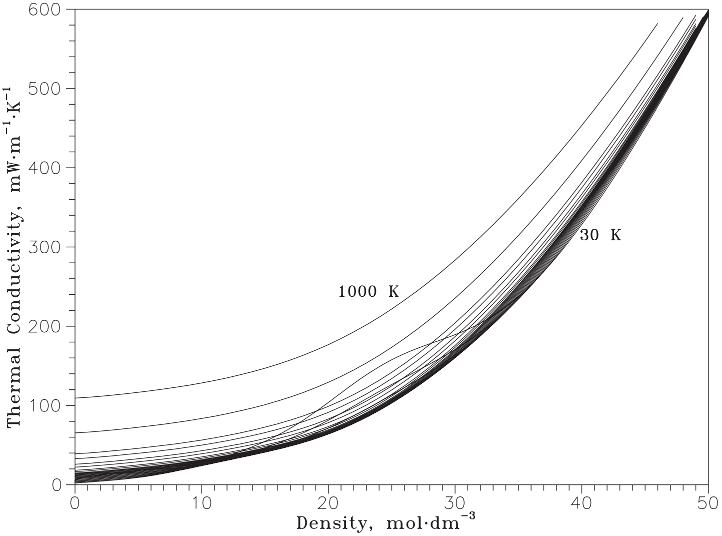

Fig. 24. Thermal conductivity versus density diagram for nitrogen showing the isotherms 30 through 160 K at every 10 K, and 180, 200, 250, 300, 400, 500, and 1000 K. (The inappropriate behavior in calculated values occurs at the lowest temperatures.)

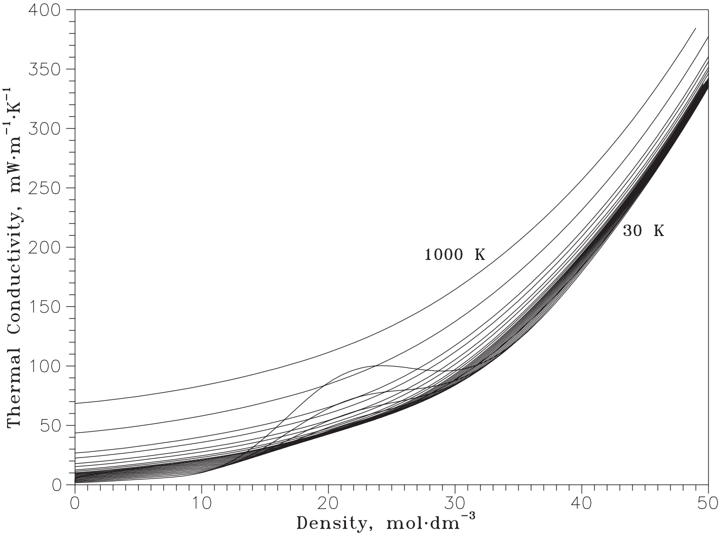

Fig. 25. Thermal conductivity versus density diagram for argon showing the isotherms 30 through 160 K at every 10 K, and 180, 200, 250, 300, 400, 500, and 1000 K. (The inappropriate behavior in calculated values occurs at the lowest temperatures.)

1 MPa and in the liquid), the uncertainties for the viscosity of nitrogen and argon are as low as 1% between 270 and 300 K at pressures less than 100 MPa, and increase outside that range. The uncertainties are about 2% at temperatures of 180 K and higher. Below this and away from the critical region, the uncertainties steadily increase to about 5% at the triple points of the fluids. The uncertainties in the critical region are higher. For oxygen and air, the uncertainties are about 2% between 270 and 300 K, and increase to 5% outside of this region. There are very few measurements between 130 and 270 K for air to validate the equations, and the uncertainties may be even higher in this supercritical region. Additionally, the uncertainty may be higher in the liquid near the triple point for oxygen.

For the thermal conductivity, the uncertainties for the dilute gas are 2% for all four fluids, with increasing uncertainties near the triple points. For the vapor region, the uncertainties for nitrogen and argon are generally about 2% for temperatures greater than 150 K for nitrogen and 170 K for argon. The uncertainty is 3% for nitrogen and argon at temperatures below the critical point and 5% in the critical region, except for states near the critical point. For oxygen, the uncertainties range from 3% between 270 and 300 K to 5% elsewhere. For air, the uncertainties range from 3% between 140 and 300 K to 5% at the triple point and at high temperatures. The uncertainties above 100 MPa are not known because of the lack of experimental data on which to base estimates.

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