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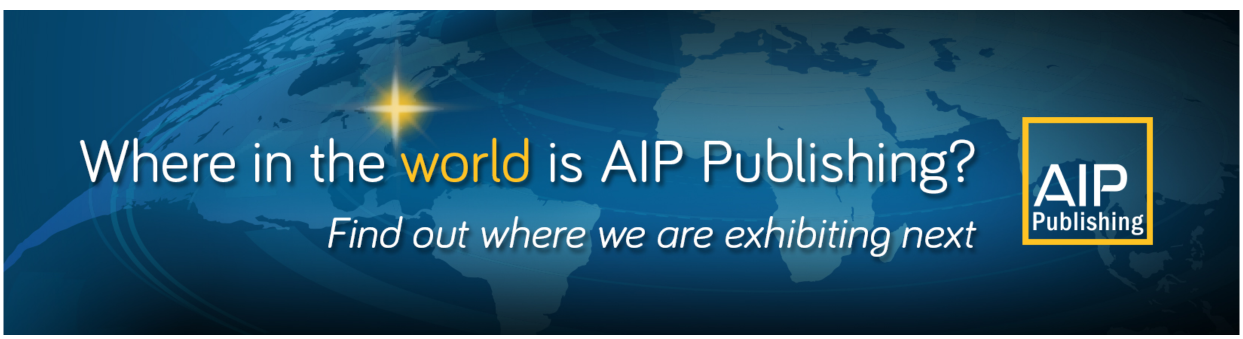

Viscosity and Thermal Conductivity of Nitrogen for a Wide Range of Fluid States

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The viscosity and the thermal conductivity of fluid nitrogen were critically evaluated and correlated on the basis of a comprehensive literature survey. Recommended values were generated in a temperature range from 70 to 1100 K and pressures up to 100 MPa using the residual concept. To retain consistency with the IUPAC Thermodynamic Tables, the same thermodynamic key data were used. Additionally, a so-called transport equation of state was established that makes it possible to achieve a unified representation of the viscosity and thermal conductivity in terms of pressure and temperature.

Key words: correlation; dilute-gas function; evaluation; excess function; fluid state; nitrogen; recommended values; thermal conductivity; transport equation of state; viscosity.

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1. Introduction

Nitrogen is the main constituent of air and hence a fluid of high technological interest in the chemical and process industry. Its thermophysical properties are needed to a high degree of accuracy. A comprehensive compilation of the thermodynamic properties of nitrogen was published by the IUPAC Thermodynamic Tables Project in 1979. The results appeared as Volume 6 of the International Thermodynamic Tables of the Fluid State.[1] In order to complete our knowledge of the thermophysical behavior of nitrogen, its transport properties, viscosity, and thermal conductivity were reevaluated because the existing compilations and correlations show fairly high discrepancies and new measurements were carried out recently.

All equations used to calculate the recommended values are formulated as FORTRAN routines in Appendices A and B. The references and the original data used in this work are an excerpt from the MIDAS data bank.[2]

2. Thermodynamic Key Data

The evaluation of the transport properties requires the knowledge of some basic thermodynamic data which are of general importance. Such data are the parameters of the gas–liquid critical point, the parameters of the triple point, a vapor-pressure equation, and a thermal equation of state to convert the temperature and pressure coordinates of the transport properties into densities. We adopted the thermodynamic key data from the IUPAC Tables[1] for the evaluation of the transport properties of nitrogen. The parameters of the critical point are given by

$$p_c = 3.40\ \text{MPa}, \quad T_c = 126.20\ \text{K}, \quad \rho_c = 314.0\ \text{kg/m}^3.$$

The parameters of the triple point are

$$p_t = 0.0125\ \text{MPa}, \quad T_t = 63.148\ \text{K}, \quad \rho_t = 867.8\ \text{kg/m}^3.$$

The vapor-pressure equation was established by Wagner[3] whereas the equation of state was developed by Jacobsen *et al.*[4] (While this paper was being prepared, Jacobsen *et al.*[5] published a new equation of state for nitrogen with improvements mainly in the critical region. It was not found necessary to reprogram this work for the new equation.)

3. Viscosity

A large number of publications report data on the viscosity of nitrogen. After a preliminary examination, about 50 of them turned out to be suitable for an evaluation because they include data in numerical form.

The most often used experimental device is the capillary viscometer which is considered to be very accurate. An even higher precision can be achieved by the oscillating-disk and the torsional-crystal method.

The evaluation has been carried out according to the residual concept which asserts that the viscosity $\eta(\rho,T)$ at a given density ρ and a temperature T can be split into a term $\eta_0(T)$ which depends on temperature only and is equal to that at the zero-density limit (dilute-gas function) and into a residual part $\Delta\eta_R(\rho)$ (excess function) that is only density dependent, up to a certain density limit. Hence,

$$\eta(\rho,T) = \eta_0(T) + \Delta\eta_R(\rho). \tag{1}$$

In this study we did not account for the critical enhancement of the viscosity of nitrogen that has been investigated by Zozulya *et al.*[6] Their experimental results have been analyzed by Basu *et al.*[7] More detailed information about the behavior of transport properties in the vicinity of the critical point was given by Sengers.[8]

3.1 Viscosity in the Zero-Density Limit

We could find 17 experimental data sets and five compilations concerning the viscosity in the dilute-gas state. In Fig. 1 the six selected data sets used for the correlation are plotted together with the correlation function, that is the dilute-gas function, up to nearly 2200 K. This is the same expression for the viscosity of a dilute gas derived from kinetic theory as was used by Cole *et al.*[9] (see FUNCTION DV0203 in Appendix A):

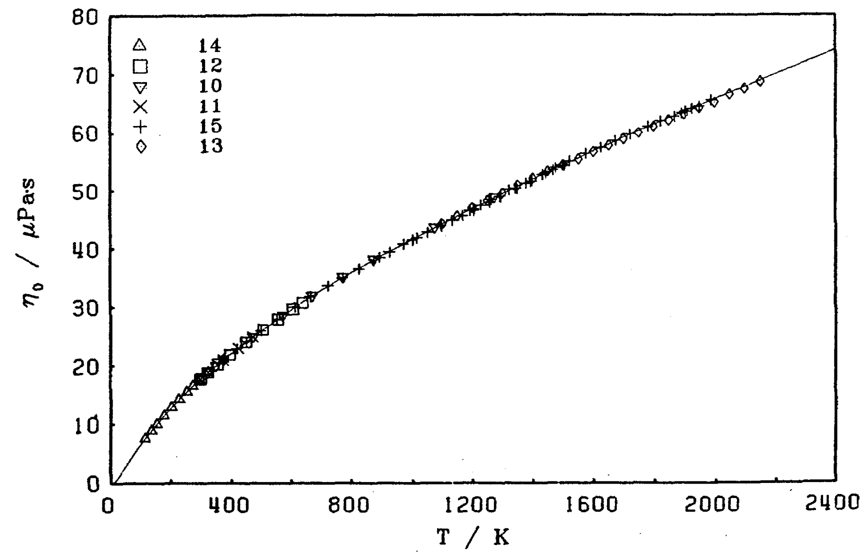

FIG. 1. Dilute-gas function for viscosity together with the selected experimental data.

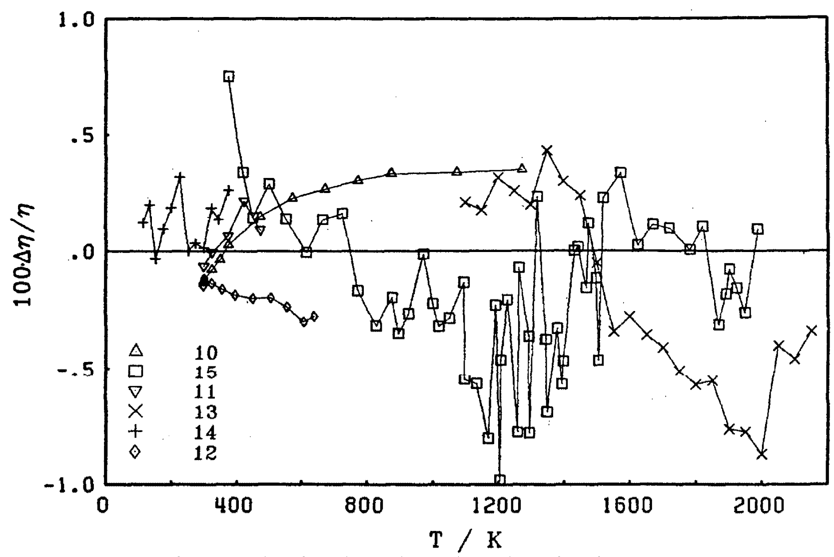

FIG. 2. Relative deviations of the selected experimental data from the dilute-gas function for viscosity.

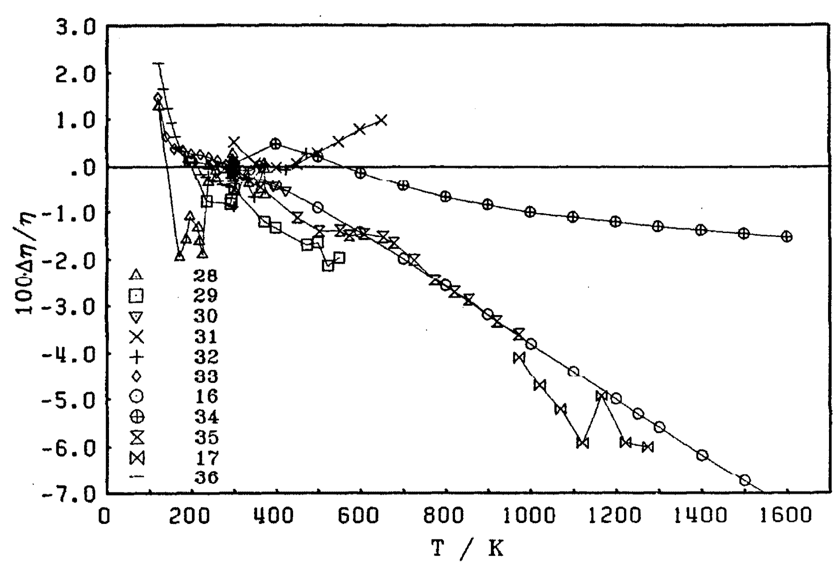

FIG. 3. Relative deviations of the rejected experimental data from the dilute-gas function for viscosity.

$$\eta_0(T) = 5/16[MkT/(\pi N_A)]^{0.5}/[\sigma^2\Omega(T^*)], \quad (2)$$

where M = molecular weight, k = Boltzmann's constant, N_A = Avogadro's number, and $\pi = 3.141\,59$. It includes the collision integral

$$\ln \Omega(T^*) = \sum_{i=0}^{4} A_i(\ln T^*)^i, \quad (3)$$

with $T^* = Tk/\epsilon$ and the energy-scaling and length-scaling parameters ϵ/k and σ as adjustable parameters. The weighted least-squares fit yielded the values $\epsilon/k = 100.01654$ K and $\sigma = 0.365\,024\,96$ nm which agree excellently with those given by Cole *et al.*[9] The parameters are listed in FUNCTION DV023 in Appendix A. Figure 2 shows the percentage deviations of the selected data sets from the present correlation function. The experimental data of Kestin *et al.*,[10,11] Vogel,[12] Guevara *et al.*,[13] Clarke *et al.*,[14] and Lavushchev *et al.*[15] could be represented by the dilute-gas function with an average deviation of 0.11% and a standard deviation of 0.33%.

Figure 3 shows the deviations of the experimental data sets which were not used for the correlation. Remarkable are the systematic deviations of the data of Bonilla *et al.*[16] and Ellis *et al.*[17]

Figure 4 compares six correlations with our new equation. It can be seen that the data of Vasserman *et al.*[18] are too low, especially at higher temperatures whereas the other correlations agree fairly well with our dilute-gas function (except at very low temperatures). A numerical comparison yielded the results compiled in Table 1.

3.2 Residual Viscosity

The pressure dependence of the viscosity of nitrogen was investigated by many authors. In all 29 publications could be used for the evaluation. There exist in addition three other correlations. In Fig. 5 the five selected data sets of Kestin *et al.*[19–21] at lower densities, Diller[22] at high densities, and Michels *et al.*[23] at medium densities are shown together with the correlation up to about 830 kg/m^3. The steep increase of the viscosity at very high densities made it impossible to correlate the excess viscosity by an ordinary polynomial in density with sufficient accuracy. Instead, we used a hyperbolic function which turned out to be successful in reproducing this extreme gradient of the viscosity at very high densities (see FUNCTION DVD203 in Appendix A):

$$\frac{\Delta\eta_R(\rho)}{\eta_c} = \frac{C_1}{(\chi - C_2)} + \frac{C_1}{C_2} + \sum_{i=3}^{5} C_i\chi^{i-2}, \quad (4)$$

where η_c represents the critical viscosity factor (Laesecke[104]) and $\chi = \rho/\rho_c$ is the reduced density. All parameters are listed in FUNCTION DVD203 in Appendix A.

Figure 6 shows the departure of the selected data sets from the present excess function. The fit yielded an average deviation of -0.027% and a standard deviation of 1.0%. At densities below 500 kg/m^3 the agreement is excellent, but the uncertainty increases to 4% at higher densities.

Figure 7 gives an impression of the discrepancies among the experimental data that were not used for the correlation. In addition to these comparisons, Table 2 also includes the deviations of some other compilations and correlations.

In Fig. 8, the viscosity surface of nitrogen, calculated by means of the dilute-gas function and the excess function, is shown over the pressure-temperature plane in a three-dimensional view including the two-phase region on the left. These data are also documented in tabular form (see Tables A1 and A2 in Appendix A). An evaluation at densities above 830 kg/m^3 seemed to be too dubious because the data of Grevendonk *et al.*,[24] van Itterbeek *et al.*,[25] Hellemans *et al.*,[26] Shepeleva *et al.*,[27] and Diller[22] in this region showed discrepancies of about 20%. New measurements seem to be needed in this region.

4. Thermal Conductivity

There exist many publications concerning the thermal conductivity of nitrogen. About 50 of them could be used for

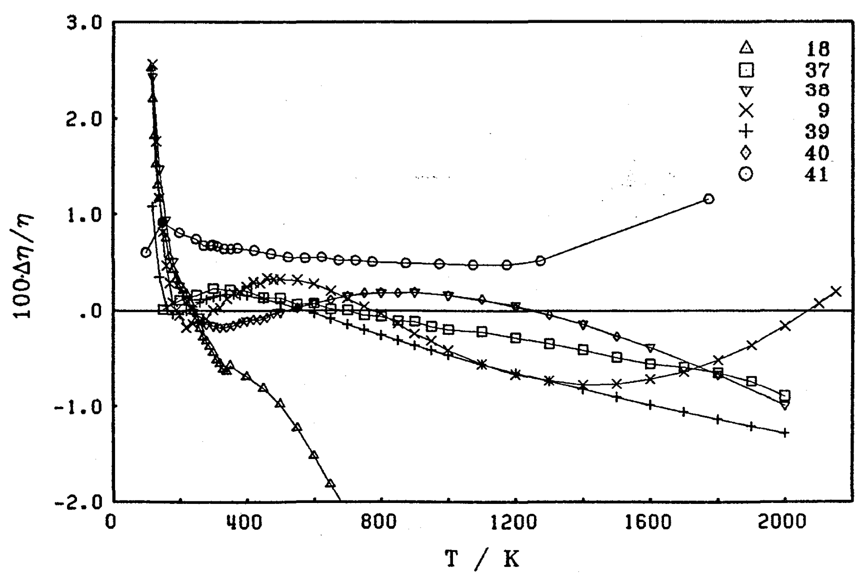

FIG. 4. Relative deviations of other compilations from the dilute-gas function for viscosity.

Table 1. Viscosity data sets compared with the dilute-gas function

Ref	author	year	me	std	neg	pos	pts	met
data used for correlation								
10	Kestin	1976	0.16	0.18	0.1	0.4	11	od
15	Lavushchev	1978	-0.16	0.33	1.0	0.8	54	ps
11	Kestin	1982	0.06	0.11	0.1	0.2	5	od
13	Guevera	1969	-0.21	0.41	0.9	0.4	22	cv
14	Clarke	1968	0.13	0.11	0.0	0.3	12	cv
12	Vogel	1984	-0.20	0.06	0.3	-	10	od
data not used for correlation								
28	Latto	1972	-0.44	0.75	1.9	1.3	25	cv
29	Ikeda	1983	-1.16	0.67	2.1	0.1	11	
30	Tsui	1959	-0.45	0.09	0.6	0.4	3	rb
31	Timrot	1969	0.40	0.36	0.0	1.0	8	od
32	Makita	1957	-0.26	0.44	0.9	0.3	6	rb
33	Clarke	1969	0.27	0.41	0.1	1.5	13	cv
16	Bonilla	1951	-4.37	3.56	12.	0.1	25	cv
34	Dawe	1970	-0.69	0.66	1.5	0.5	46	cv
35	Rigby	1965	-1.84	0.99	3.6	0.1	15	cv
17	Ellis	1959	-5.25	0.73	6.0	-	7	cv
36	Lukin	1983	0.26	0.78	0.5	2.2	18	pd
correlations/compilations								
37	Hanley	1973	-0.16	0.32	0.9	0.2	28	
38	Maitland	1972	0.18	0.71	1.0	2.5	22	
9	Cole	1984	0.07	0.62	0.8	2.6	46	
39	Matsunaga	1983	-0.30	0.46	1.3	0.7	37	
40	JSME	1983	-0.01	0.14	0.3	0.2	52	
41	Boushehri	1987	0.63	0.16	-	1.2	25	

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me= mean error (%)
std= standard deviation (%)
neg= max. negative error (%)
pos= max. positive error (%)
pts= number of points
met= method

cv = capillary viscometer
od = oscillating disk
rb = rolling ball
pd = pressure drop
ps = passing stream

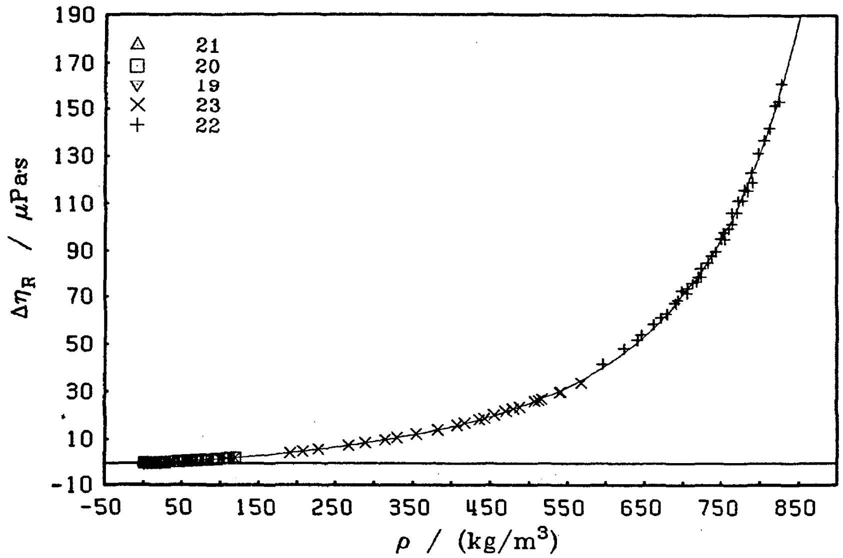

FIG. 5. Excess function for viscosity together with the selected experimental data.

an evaluation. Most of the authors used the coaxial cylinder method or the more precise hot-wire instrument. The evaluation and correlation of the thermal conductivity was carried out in the same way as for the viscosity [Eq. (1)], which means that the residual concept was used:

$$\lambda(\rho,T) = \lambda_0(T) + \Delta\lambda_R(\rho). \tag{5}$$

We did not account for the critical enhancement of the thermal conductivity of nitrogen because of the lack of experimental data in the vicinity of the critical point. Detailed information about the calculation of the thermal conductivity in the critical region is given by Hanley *et al.*[58] Recommendations for the calculation of the thermal conductivity near the critical point can also be found in the review of Sengers.[8]

4.1 Thermal Conductivity in the Zero-Density Limit

The thermal conductivity of a polyatomic gas is usually considered to consist of a contribution due to the translational energy transfer λ_{tr} and a contribution due to the internal degrees of freedom of the molecule λ_{in}. Then

$$\lambda_0(T) = \lambda_{tr} + \lambda_{in}. \tag{6}$$

In order to describe the thermal conductivity of nitrogen in the dilute-gas region we used, therefore, the expressions for polyatomic gases derived from the kinetic theory by Wang Chang *et al.*[59] and discussed by Maitland *et al.*[60] (see FUNCTION TC0203 in Appendix B):

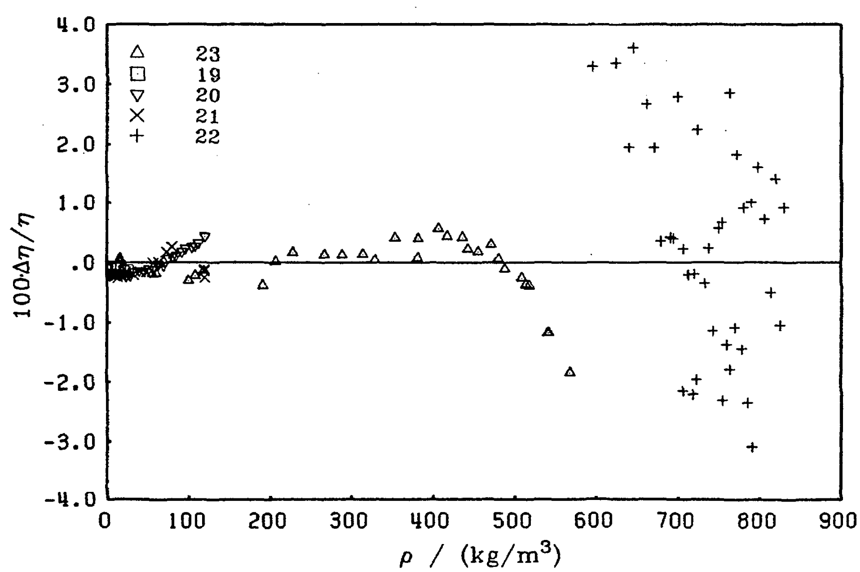

FIG. 6. Relative deviations of the selected experimental data from the excess function for viscosity.

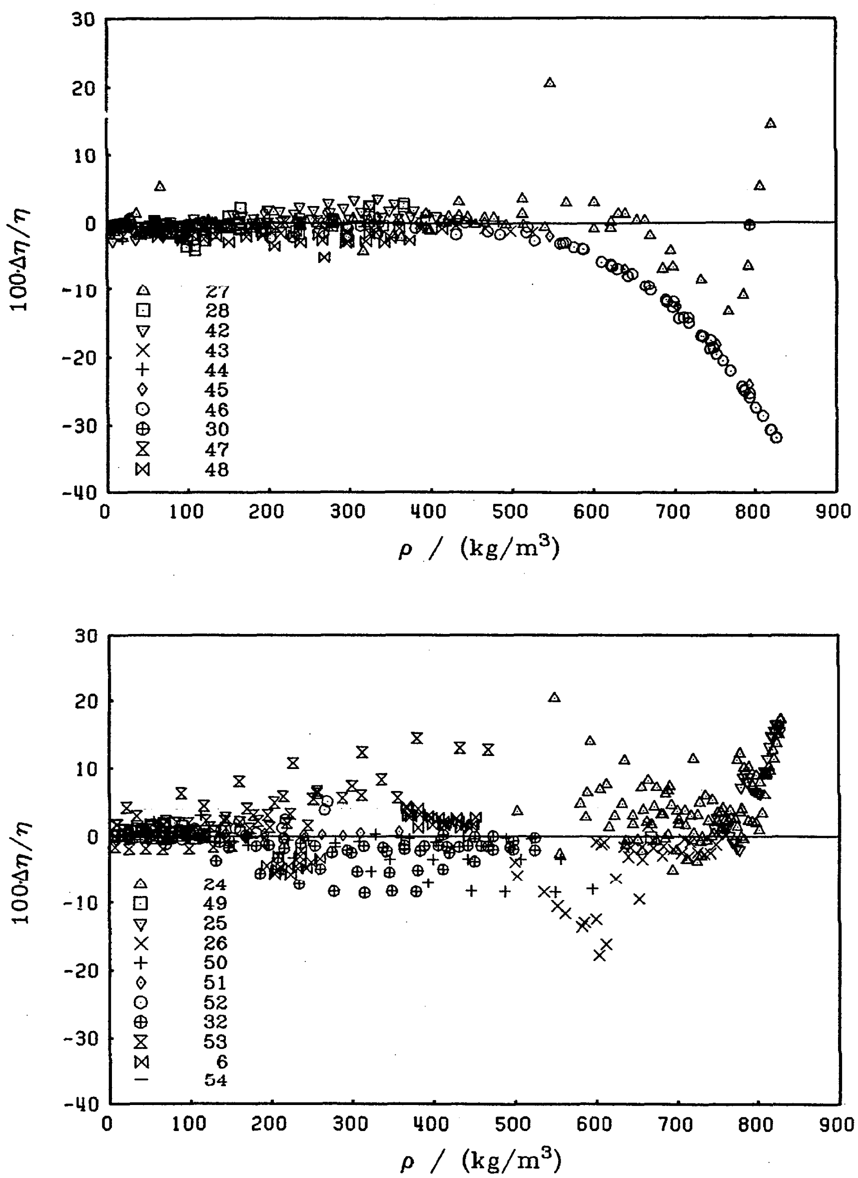

FIG. 7. Relative deviations of the rejected experimental data from the excess function for viscosity.

$$\lambda_{tr} - 2.5F(1.5 - X_1), \quad (7)$$

$$\lambda_{in} = FX_2[c_{v0}(T)/(kN_A) + X_1], \quad (8)$$

with the adjustable parameters $X_1 = 0.951\,852\,02$ and $X_2 = 1.020\,542\,2$ and

$$F = kN_A \eta_0(T)/M. \quad (9)$$

In this semiclassical theory a relationship between the thermal conductivity and the viscosity in the dilute-gas state was established. Consequently, to achieve consistency the corresponding correlation function for the viscosity $\eta_0(T)$ discussed earlier was also employed here. The ideal isochoric heat capacity $c_{v0}(T)$, also needed in the dilute-gas function for thermal conductivity, was calculated with the appropriate expression from the IUPAC Tables[1] (see FUNCTION CVIDEAL in Appendix B):

In Fig. 9 the seven selected data sets used for the correlation are shown together with the dilute-gas function up to a temperature of about 2400 K. We used the weighted data of Keyes,[61] Slyusar *et al.*,[62] Clifford *et al.*,[63] Chen *et al.*,[64] Westenberg *et al.*,[65] and Yorizane *et al.*[66] Above a temperature of about 1200 K there exist no data of high reliability. Nevertheless, in order to extend the range of the dilute-gas function for thermal conductivity to higher temperatures, matching those for viscosity, we included the data of Chen *et al.*,[64] but gave them the smallest weight.

Figure 10 shows the deviations of the selected data sets from the present correlation. The experimental data could

Table 2. Viscosity data sets compared with the excess function

Ref	author	year	me	std	neg	pos	pts	met
data used for correlation								
23	Michels	1953	-0.09	0.50	1.8	0.6	33	cv
19	Kestin	1968	-0.10	0.03	0.1	-	6	od
20	Kestin	1971	-0.06	0.19	0.2	0.4	33	od
22	Diller	1982	0.33	1.81	3.1	3.6	39	tc
21	Kestin	1959	-0.13	0.14	0.3	0.3	20	od
data not used for correlation								
27	Shepeleva	1971	0.04	4.85	13.	20.	56	cv
28	Latto	1972	-0.70	1.10	4.0	2.9	81	cv
42	Baron	1959	0.71	1.55	2.7	3.6	40	cv
43	Chierci	1969	-0.66	0.47	1.7	0.2	12	cv
44	Kao	1967	-0.30	0.65	2.3	1.1	35	cv
45	Schlumpf	1975	-5.89	9.23	24.	1.6	10	cv
46	Golubev	1974	-10.2	10.1	32.	0.4	66	cv
30	Tsui	1959	-0.27	0.24	0.6	0.6	29	rb
47	Gracki	1969	-0.42	0.44	1.9	0.5	46	cv
48	Reynes	1966	-2.07	0.91	5.1	0.8	30	cv
24	Grevendonk	1970	4.52	5.03	5.0	20.	101	tc
49	Kestin	1963	0.71	0.62	0.4	2.0	37	od
25	v. Itterbeek	1966	7.42	6.04	1.9	17.	31	od
26	Hellemans	1970	-4.68	5.06	18.	1.6	35	od
50	Ross	1957	-1.67	2.86	8.4	3.1	41	cv
51	Flynn	1963	-0.08	0.40	1.0	0.8	34	cv
52	Goldman	1963	1.18	1.57	0.5	5.1	16	cv
32	Makita	1957	-2.41	2.38	8.6	0.9	54	rb
53	Makavetskas	1963	3.03	3.88	1.9	14.	62	cv
6	Zozulya	1975	-0.15	3.42	5.6	4.4	38	od
54	Kobayashi	1977	-0.45	0.18	0.6	0.1	6	cv
- saturated liquid -								
55	Foerster	1963	21.3	4.73	-	30.	8	od
56	Rudenko	1939	32.4	15.3	-	48.	6	oc
57	Boon	1967	15.6	1.90	-	18.	4	cv
correlations/compilations								
18	Vasserman	1970	-1.11	2.64	8.4	14.	1081	
58	Hanley	1974	0.07	1.68	11.	4.3	196	
40	JSME	1983	-0.70	0.57	2.3	0.2	418	

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me= mean error (%)
std= standard deviation (%)
neg= max. negative error (%)
pos= max. positive error (%)
pts= number of points
met= method

cv = capillary viscometer
oc = oscillating cylinder
od = oscillating disk
rb = rolling ball
tc = torsional crystal

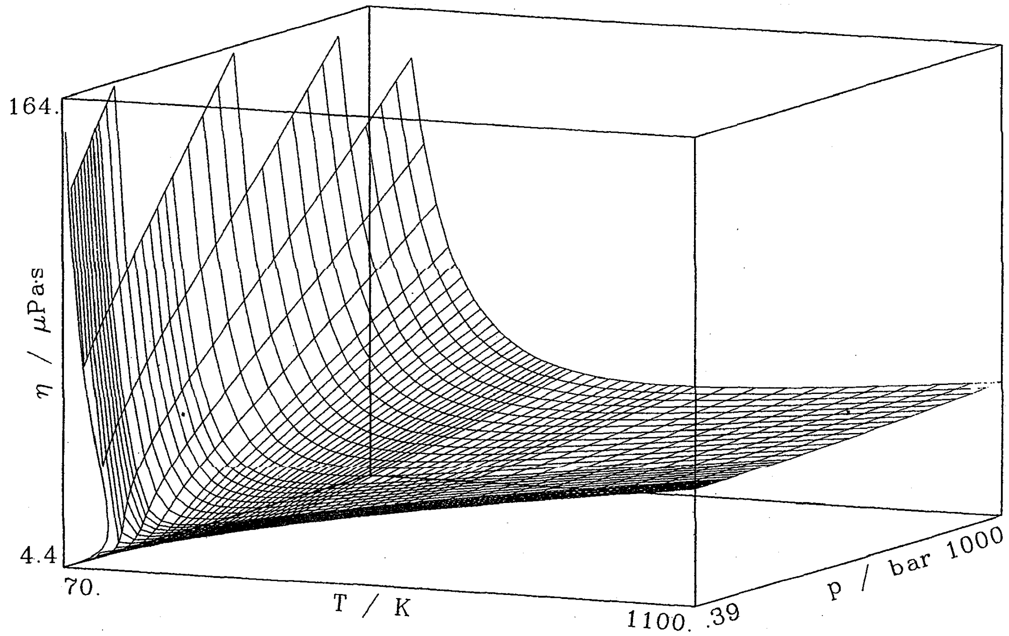

FIG. 8. Viscosity surface over the pressure-temperature plane.

be fitted with an average deviation of − 0.0058% and a standard deviation of 0.77%.

Figure 11 shows departure plots of the experimental data sets that were rejected. Extreme deviations are apparent for the data sets of Keyes *et al.*,[67] Schaefer *et al.*,[68] Geier *et al.*,[69] and Schottky.[70] In Fig. 12 eleven correlations or compilations are seen compared with our dilute-gas function. It can be seen that the equations of Matsunaga *et al.*[39] and Hanley *et al.*[58] agree fairly well with our correlation. These results are also compiled in Table 3.

In order to check the reliability and consistency of the dilute-gas functions for viscosity η_0 and thermal conductivity λ_0 we calculated the Eucken factor using the dimensionless expression $\lambda_0 M/(\eta_0 c_{v0})$, where c_{v0} stands for the ideal isochoric heat capacity and M represents the molecular weight. In case of nonpolar gases this value lies between the conventional Eucken factor and the so called modified Eucken factor (Reid *et al.*,[71] Chap. 10–3). This is confirmed in Fig. 13 where the solid line represents our calculated Eucken factor as a function of temperature. The conventional and the modified Eucken factor are drawn as a dash–dot line and a broken line, respectively.

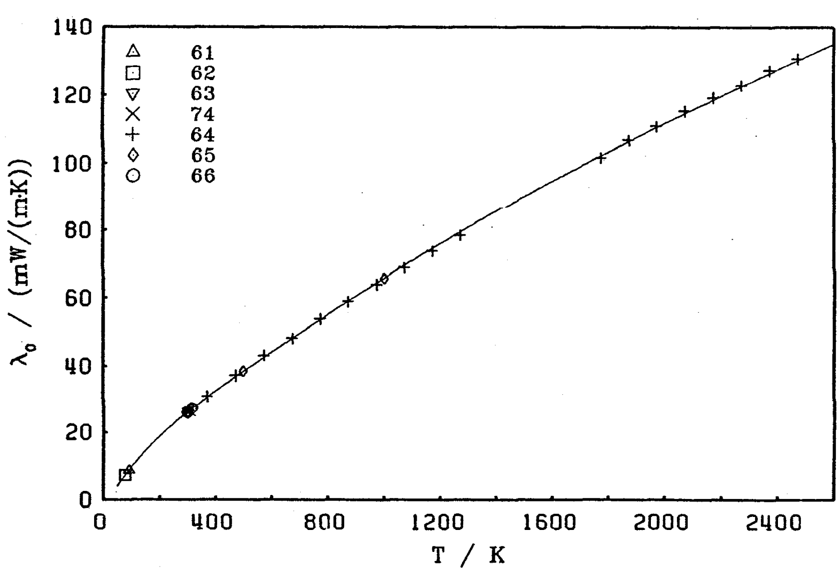

FIG. 9. Dilute-gas function for thermal conductivity together with the selected experimental data.

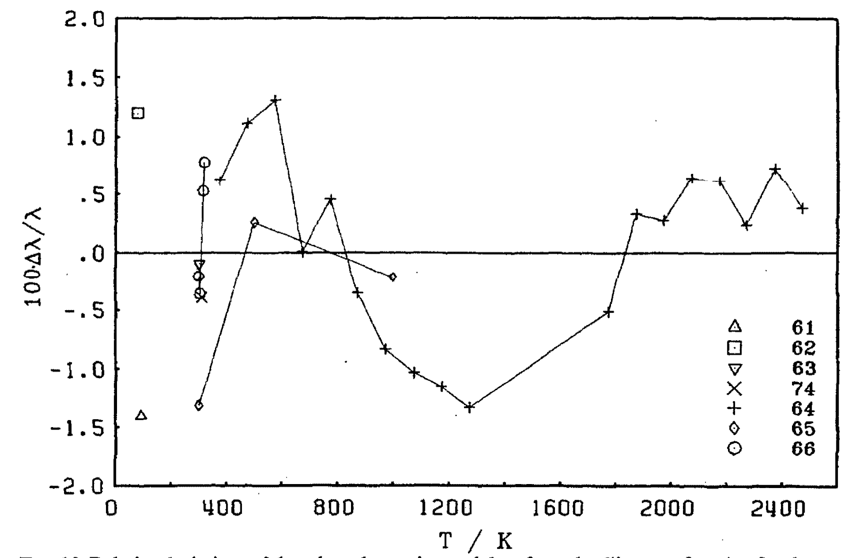

FIG. 10. Relative deviations of the selected experimental data from the dilute-gas function for thermal conductivity.

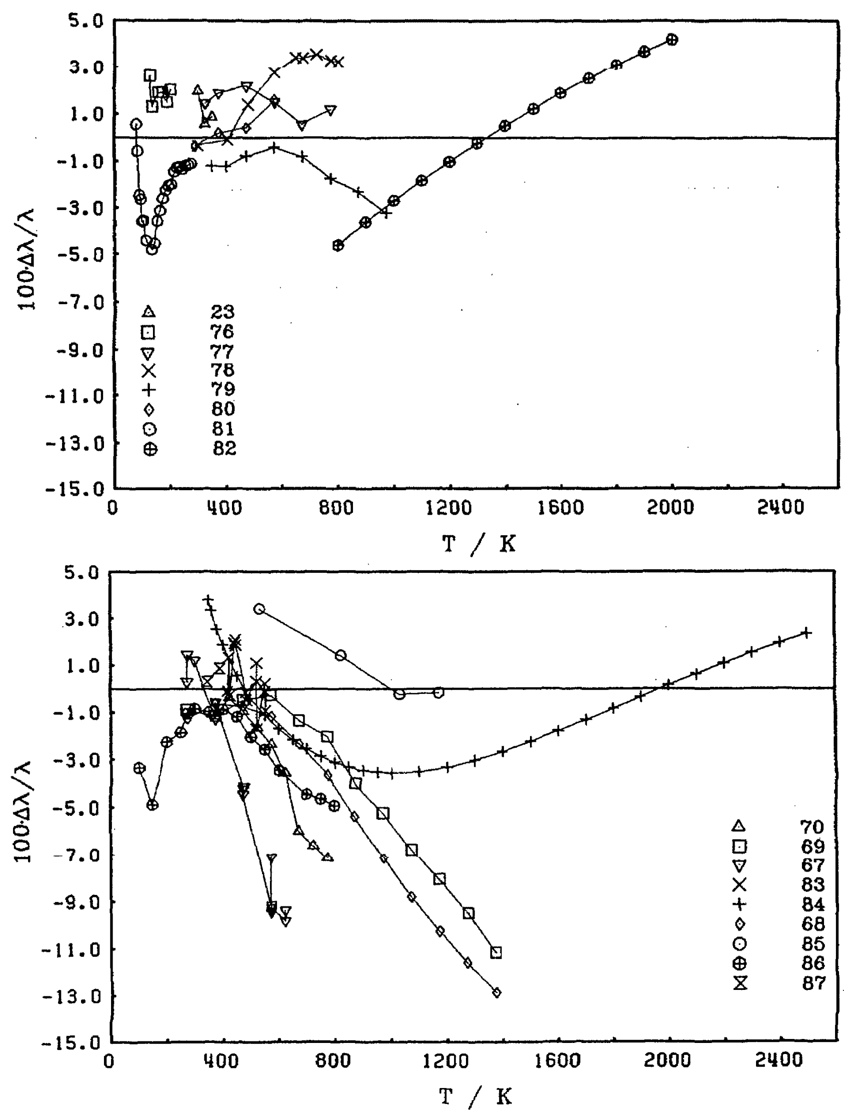

FIG. 11. Relative deviations of the rejected experimental data from the dilute-gas function for thermal conductivity.

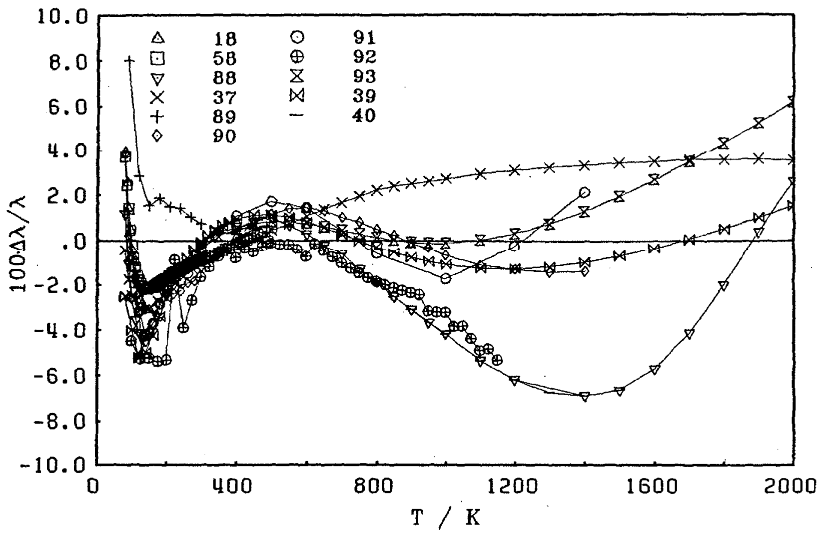

FIG. 12. Relative deviations of other compilations from the dilute-gas function for thermal conductivity.

4.2. Residual Thermal Conductivity

The pressure dependence of nitrogen was investigated very often. In all 26 publications could be used for the evaluation and correlation of the residual thermal conductivity of nitrogen. Besides this four correlations could be found.

In Fig. 14 the selected data sets for the correlation are plotted up to a density of about 1100 kg/m^3, together with the excess function

$$\Delta\lambda_R(\rho)/\lambda_c = \sum_{i=1}^{4} C_i \chi^i. \tag{10}$$

Here, λ_c is the critical thermal conductivity factor and $\chi = \rho/\rho_c$ is the reduced density. All parameters are listed in FUNCTION TCD203 in Appendix A.

It can be seen that in the high-density region the data of Tufeu *et al.*[72] were used. In the region between 350 and 500 kg/m^3 we selected the data of Roder[73] whereas in the region of lower density the data of Clifford *et al.*,[63] Assael *et al.*,[74] and Haran *et al.*[75] are dominant, as can be seen from Fig. 15 in which the corresponding deviations are plotted. The fit yielded an average deviation of -0.087% and a standard deviation of 1.1%. Figure 16 gives an impression of the scatter of the rejected data. The deviations reach values as high as 20%. In addition to these graphical results, Table 4 shows also the deviations from other correlations and compilations.

In Fig. 17 the new recommended values, also documented in Tables B1 and B2 in Appendix B, are plotted in a three-dimensional view over the pressure-temperature plane with the saturation line on the left. The temperature scale covers the range from 70 to 1100 K at pressures up to 100 MPa.

5. Transport Equation of State

In addition to the conventional method of correlating transport properties by the use of the residual concept we have developed a so-called transport equation of state (TEOS) to represent the viscosity and thermal conductivity as direct functions of pressure and temperature (Laesecke[104]). This concept offers the advantage that transport properties can be correlated and calculated without the need of a thermal equation of state.

The study of a suitable functional form for such a transport equation of state was based on a phenomenological analysis of the surfaces of viscosity and thermal conductivity in terms of pressure and temperature, as shown before. It turned out that the transport properties, covering the entire fluid region, could be represented successfully only with pressure as the dependent variable and temperature and transport property as independent variables. In this representation singularities do not exist. The TEOS for both transport properties (TP) reads

$$\pi = \sum_{i=1}^{6} [A_i(T)\psi^i] + [A_7(T)\psi^3 + A_8(T)\psi^5]\exp(-I\psi^2), \tag{11}$$

with the eight temperature functions

$$A_1(T) = \frac{a_1}{\tau^{0.5}} + a_2\tau^{0.5} + a_3\tau + a_4\tau^{1.5} + a_5\tau^2, \tag{12}$$

$$A_2(T) = a_6 + a_7\tau + a_8\tau^{1.5} + a_9\tau^2, \tag{13}$$

$$A_3(T) = a_{10}\tau^{0.5} + a_{11}\tau + a_{12}\tau^2, \tag{14}$$

$$A_4(T) = a_{13}\tau + a_{14}\tau^2, \tag{15}$$

$$A_5(T) = a_{15}\tau^2, \tag{16}$$

$$A_6(T) = a_{16}\tau^2, \tag{17}$$

$$A_7(T) = a_{17} + a_{18}\tau + a_{19}\tau^2, \tag{18}$$

Table 3. Thermal conductivity data sets compared with the dilute-gas function

Ref	author	year	me	std	neg	pos	pts	met
data used for correlation								
61	Keyes	1955	-1.40	-	1.4	-	1	cc
62	Slusar	1975	1.20	-	-	1.2	1	hw
63	Clifford	1979	-0.09	-	0.0	-	1	hw
64	Chen	1973	-0.49	1.47	4.2	1.3	22	hw
65	Westenberg	1962	-0.42	0.80	1.3	0.3	3	hw
66	Yorizane	1983	0.19	0.55	0.4	0.8	4	cc
Data not used for correlation								
23	Michels	1953	1.15	0.74	-	2.0	3	pp
76	Ziebland	1958	1.88	0.46	-	2.6	6	cc
77	Nuttal	1957	1.47	0.57	-	2.2	6	pp
78	Le Neindre	1971	2.31	1.57	0.3	3.6	9	cc
79	Johannin	1958	-1.45	0.93	3.2	-	8	cc
80	Stolyarov	1950	0.47	0.82	0.4	1.6	4	cc
81	Golubev	1964	-2.29	1.39	4.8	0.6	22	cc
82	Faubert	1972	0.24	2.86	4.6	4.2	13	hw
70	Schottky	1952	-3.31	2.63	7.2	-	9	hw
69	Geier	1961	-4.24	3.84	11.	-	12	hw
67	Keyes	1950	-4.43	4.30	10.	1.5	15	cc
83	Brain	1967	0.37	1.14	1.7	2.1	14	cc
84	Saxena	1975	-0.87	2.29	3.6	3.8	31	hw
68	Schaefer	1957	-5.48	4.52	13.	-	12	hw
85	Vines	1960	1.11	1.72	0.2	3.4	4	cc
86	Franck	1951	-2.62	1.54	4.9	-	15	hw
87	Clifford	1981	0.84	0.59	-	1.3	2	hw
Correlations/compilations								
18	Vasserman	1970	-0.98	2.28	3.1	4.0	14	
58	Hanley	1974	-0.87	1.11	2.2	3.7	64	
88	Touloukian	1970	-1.29	3.34	6.9	7.1	43	
37	Hanley	1973	0.79	2.22	3.1	3.6	38	
89	Zimina	1978	2.36	2.37	-	8.1	8	
90	Vargaftik	1978	-1.02	1.89	5.0	3.8	37	
91	Ziebland	1981	-0.81	2.10	4.2	3.8	19	
92	Gamphir	1967	-2.25	1.79	5.4	-	43	
93	Mito	1985	2.57	3.48	0.3	11.	30	
39	Matsunaga	1983	-0.75	1.73	5.2	1.5	39	
40	JSME	1983	-1.54	2.72	6.9	1.0	26	

----

me= mean error (%)
std= standard deviation (%)
neg= max. negative error (%)
pos= max. positive error (%)
pts= number of points
met= method

cc = coaxial cylinder
hw = hot wire
pp = parallel plate

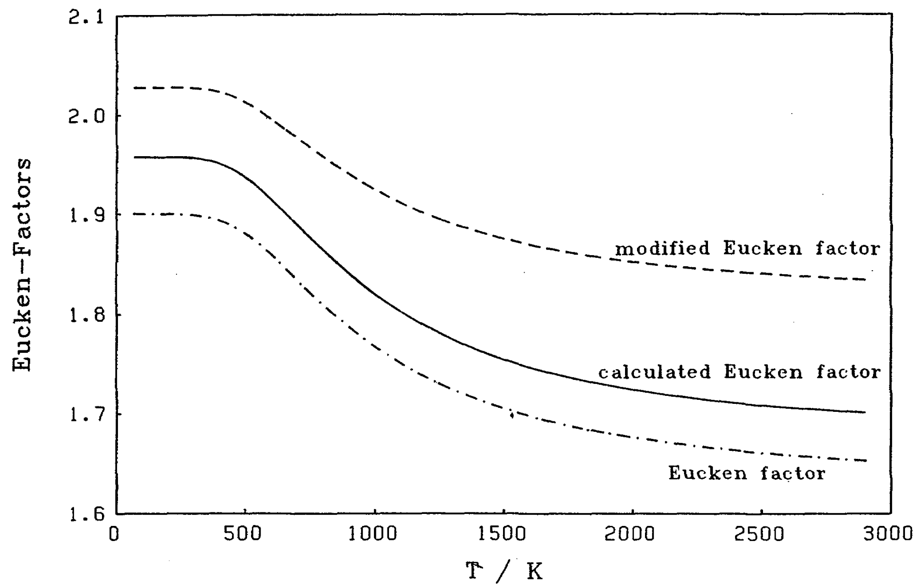

FIG. 13. Intercomparison of the Eucken factors.

$$A_8(T) = a_{20}\tau^{0.5} + a_{21}\tau^{2.5}. \quad (19)$$

The term

$$\psi = \ln(TP/TP_c + 1) \quad (20)$$

represents either the reduced viscosity or the reduced thermal conductivity, whereas $\pi = p/p_c$ and $\tau = T/T_c$ stand for the reduced pressure and the reduced temperature, respectively.

The parameters a_1 to a_{21} [written as a(1) − a(21) in the computer output], the exponential-function exponent I and the critical viscosity and thermal conductivity factors TP_c (Laesecke[104]) are compiled in Table C1 and C2 in Appendix C. This TEOS was used to represent both the viscosity and the thermal conductivity.

The corelation of the viscosity data yielded a mean error of 0.165%, a standard deviation of 1.15% and an absolute mean error of 0.8%. The departure surface, i.e., the deviations of the transport equation of state from the recommended values, is shown in Fig. 18. The shape of the deviation surface suggests that the transport equation of state is deficient at very low temperatures and in the vicinity of the critical point. However, it seems that reliable extrapolations can be expected at high temperatures and high pressures. Some representative isotherms from 100 to 1100 K are shown in Fig. 19 together with the recommended values and

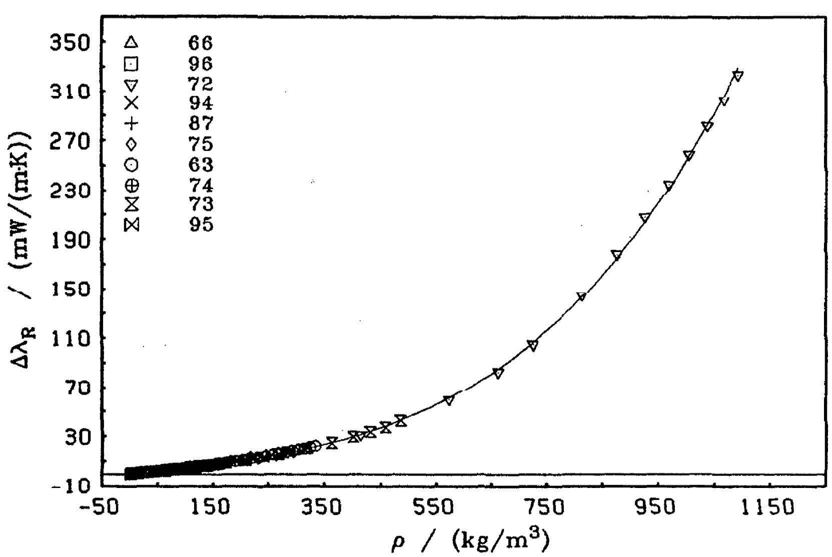

FIG. 14. Excess function for thermal conductivity together with the selected experimental data.

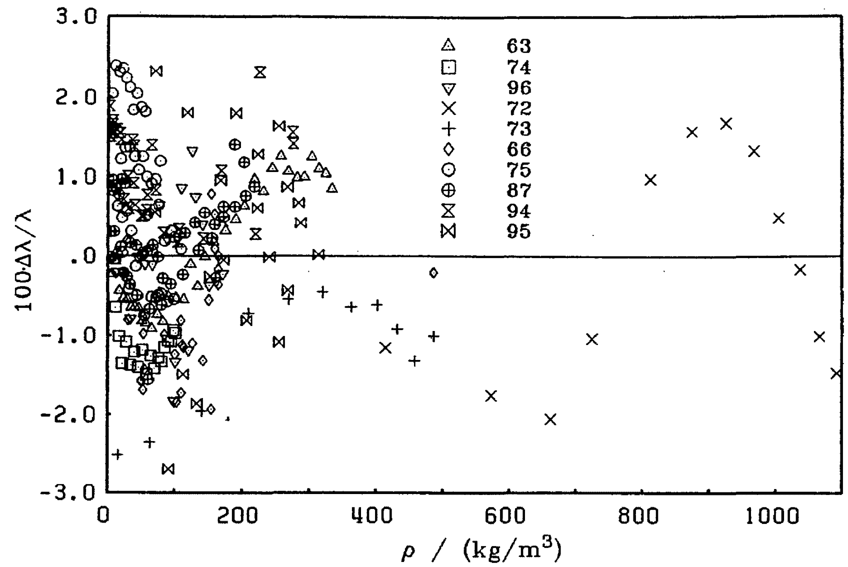

FIG. 15. Relative deviations of the selected experimental data from the excess function for thermal conductivity.

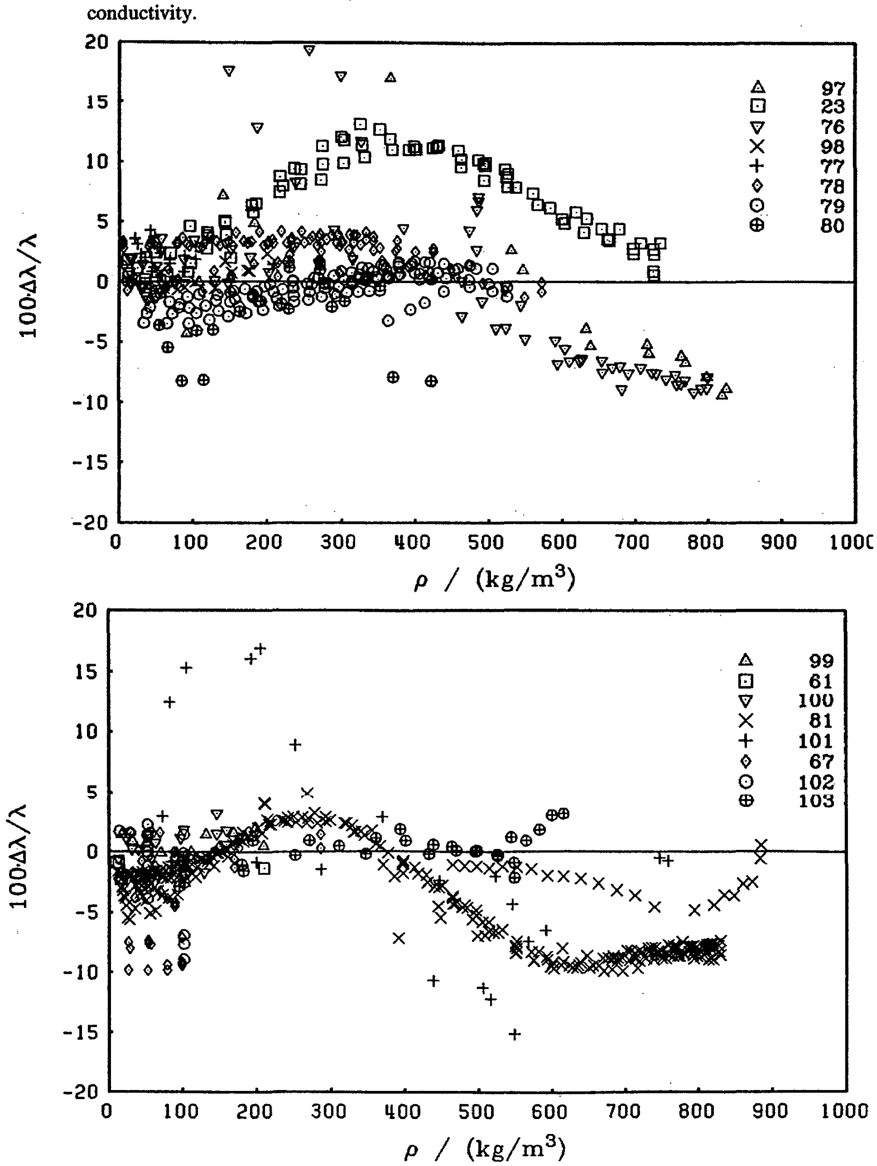

FIG. 16. Relative deviations of the rejected experimental data from the excess function for thermal conductivity.

Table 4. Thermal conductivity data sets compared with the excess function

Ref	author	year	me	std	neg	pos	pts	met
data used for correlation								
94	Keyes	1965	1.08	0.58	–	2.3	31	cc
95	Misic	1965	0.20	1.29	2.7	2.3	21	cc
63	Clifford	1979	0.09	0.76	0.9	1.3	34	hw
74	Assael	1981	-1.18	0.21	1.5	–	18	hw
96	Zheng	1984	-0.14	0.80	1.8	1.3	18	cc
72	Tufeu	1980	-0.16	1.32	2.1	1.7	13	cc
73	Roder	1959	-1.18	0.75	2.5	–	11	hw
66	Yorizane	1983	-0.73	0.74	1.9	0.8	28	cc
75	Haran	1983	0.80	0.95	0.7	2.4	45	hw
87	Clifford	1981	0.22	0.59	1.6	1.4	41	hw
data not used for correlation								
97	Uhlir	1952	-1.81	6.86	9.4	17.	17	cc
23	Michels	1953	6.37	3.87	0.2	13.	81	pp
76	Ziebland	1958	1.26	9.42	9.1	36.	86	cc
98	Lenoir	1951	0.44	1.01	0.8	2.4	13	cc
77	Nuttal	1957	2.06	1.14	–	4.3	18	pp
78	Le Neindre	1971	2.57	1.36	1.3	4.2	108	cc
79	Johannin	1958	-0.50	1.33	3.5	1.7	114	cc
80	Stolyarov	1950	-2.39	3.19	8.2	1.7	24	cc
99	Lenoir	1953	0.87	0.67	0.0	2.0	13	cc
61	Keyes	1955	-1.36	0.62	2.2	0.9	4	cc
100	Keyes	1951	1.00	1.21	1.7	3.2	13	cc
81	Golubev	1964	-4.31	3.95	9.9	5.0	321	cc
101	Borovik	1947	-0.04	9.43	15.	17.	21	pp
67	Keyes	1950	-3.43	3.98	9.8	1.6	40	cc
102	Tufeu	1979	-1.34	3.42	8.9	2.3	18	cc
103	Mosczynski	1973	0.03	1.52	2.8	3.1	29	cc
correlations/compilations								
18	Vasserman	1970	-7.42	2.02	9.4	4.0	411	
58	Hanley	1974	0.62	4.79	11.	56.	1235	
90	Vargaftik	1978	-1.73	3.14	11.	4.0	820	
40	JSME	1983	-1.62	2.73	7.1	1.9	494	

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me= mean error (%)
std= standard deviation (%)
neg= max. negative error (%)
pos= max. positive error (%)
pts= number of points
met= method

cc = coaxial cylinder
hw = hot wire
pp = parallel plate

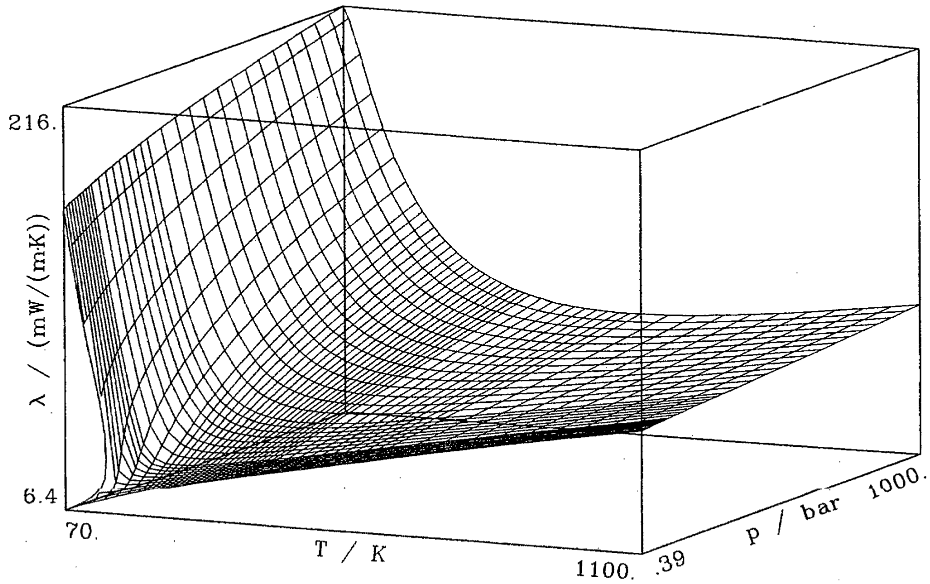

FIG. 17. Thermal conductivity surface over the pressure-temperature plane.

the saturation line. To demonstrate the similarity to the density the undercritical isotherms were drawn throughout the two-phase region. It can be seen that there exists a minimum and a maximum.

The thermal conductivity can be calculated from the same equation, but with different parameters a_1–a_{21}. In Fig. 20 the departure surface of the thermal conductivity of nitrogen is plotted as a function of pressure and temperature. It can be seen that the equation of state yields values of thermal conductivity which are too high at temperatures near the triple point. Except for the critical region, the remaining part of the surface is very smooth and flat. The transport equation of state represents the recommended thermal conductivity with a mean error of -0.01%, a standard deviation of 0.83% and an absolute mean error of 0.4%. In Fig. 21 some representative isotherms are plotted together with the recommended values and the saturation line.

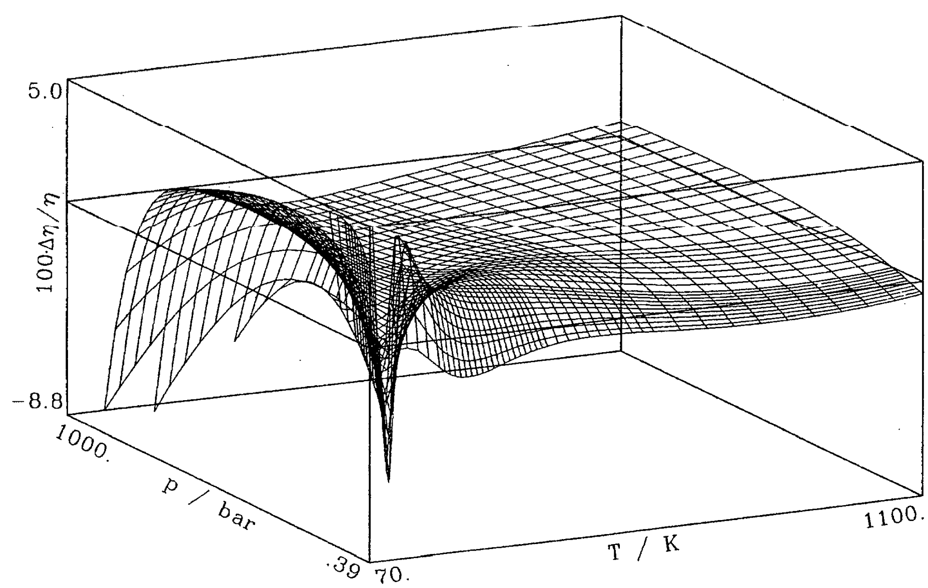

FIG. 18. Departure surface resulting from a comparison of the TEOS for viscosity with the recommended values.

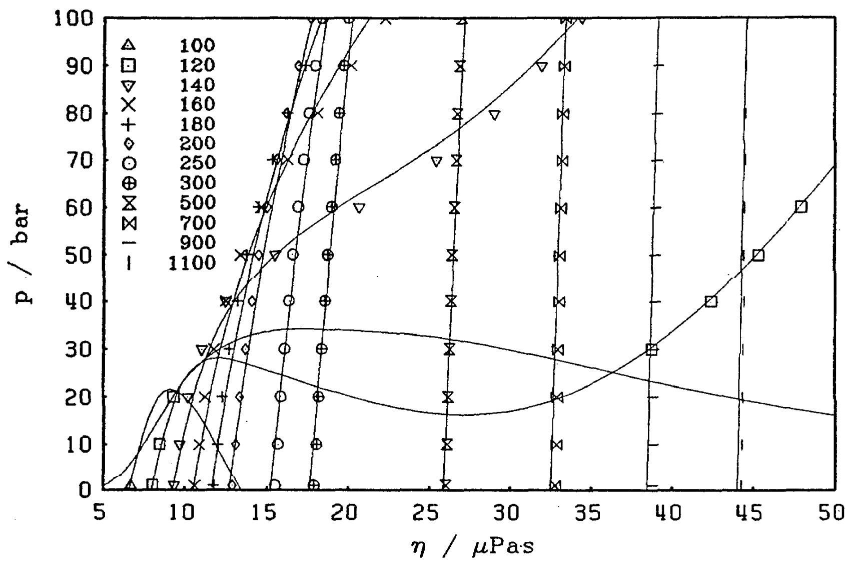

FIG. 19. Isotherms of the TEOS from 100 to 1100 K (full lines) together with the recommended viscosity values (symbols) and the saturation line.

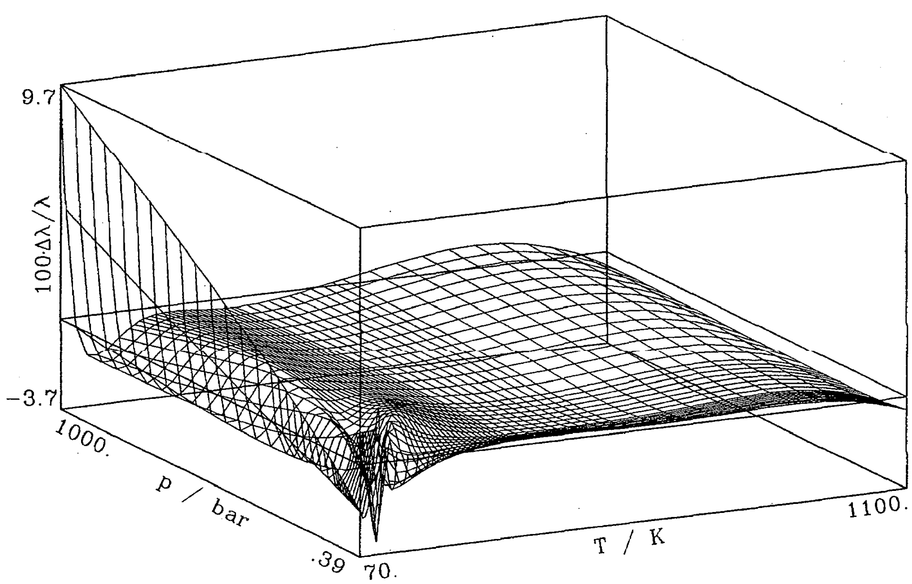

FIG. 20. Departure surface resulting from a comparison of the TEOS for thermal conductivity with the recommended values.

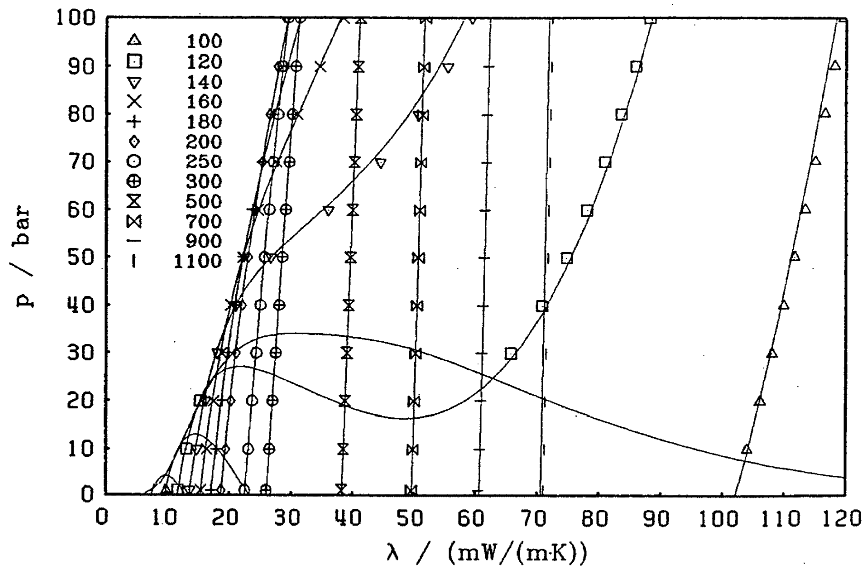

FIG. 21. Isotherms of the TEOS from 100 to 1100 K (full lines) together with the recommended thermal conductivity values (symbols) and the saturation line.

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7. References

[1]S. Angus, K. M. de Reuck, B. Armstrong, R. T. Jacobsen, and R. B. Stewart, *International Thermodynamic Tables of the Fluid State-6 Nitrogen,* International Union of Pure and Applied Chemistry, Chemical Data Series No. 20 (Pergamon, Oxford, 1979).
[2]A. Laesecke, K. Stephan, and R. Krauss, Int. J. Thermophys. **4**, 973 (1986).
[3]W. Wagner, Fortschr. Ber. VDI Z. **3**, 39 (1974).
[4]R. T. Jacobsen and R. B. Stewart, J. Phys. Chem. Ref. Data **2**, 757 (1973).
[5]R. T. Jacobsen, R. B. Stewart, and M. Jahangiri, J. Phys. Chem. Ref. Data **2**, 735 (1986).
[6]V. N. Zozulya and Y. P. Blagoi, Sov. Phys. JETP **3**, 99 (1974).
[7]R. S. Basu and J. V. Sengers, J. Heat Transf. **101**, 3 (1979).
[8]J. V. Sengers, Int. J. Thermophys. **6**, 203 (1985).
[9]W. A. Cole and W. A. Wakeham, J. Phys. Chem. Ref. Data **14**, 209 (1985).
[10]J. Kestin and S. T. Ro, Ber. Bunsenges. Phys. Chem. **80**, 619 (1976).
[11]J. Kestin, S. T. Ro, and W. A. Wakeham, Ber. Bunsenges. Phys. Chem. **86**, 753 (1982).
[12]E. Vogel, Ber. Bunsenges. Phys. Chem. **88**, 997 (1984).
[13]F. A. Guevara, B. B. McInteer, and W. E. Wageman, Phys. Fluids **12**, 2493 (1969).
[14]A. G. Clarke and E. B. Smith, J. Chem. Phys. **48**, 3988 (1968).
[15]A. V. Lavushchev and V. E. Lyusternik, Teplofiz. Vys. Temp. **16**, 209 (1978).
[16]C. F. Bonilla, R. I. Brookes, and P. L. Walker, in "Proceedings of the General Discussion on Heat Transfer" (Institution of Mechanical Engineers, London, 1951), p. 162.
[17]C. P. Ellis and C. J. G. Raw, J. Chem. Phys. **30**, 574 (1959).
[18]A. A. Vasserman and V. A. Rabinovich, *Thermophysical Properties of Liquid Air and its Components* (IPST, Jerusalem, 1970).
[19]J. Kestin and J. Yata, J. Chem. Phys. **49**, 4780 (1968).
[20]J. Kestin, E. Paykoc, and J. V. Sengers, Physica **54**, 1 (1971).
[21]J. Kestin and W. Leidenfrost, Physica **25**, 1033 (1959).
[22]D. E. Diller, Physica **119A**, 92 (1983).
[23]A. Michels and A. Botzen, Physica **19**, 585 (1953).
[24]W. Grevendonk, W. Herreman, and A. de Bock, Physica **46**, 600 (1970).
[25]A. van Itterbeek, J. Hellemans, H. Zink, and M. van Cauteren, Physica **32**, 2171 (1966).
[26]J. Hellemans, H. Zink, and O. Van Paemel, Physica **47**, 45 (1970).
[27]R. I. Shepeleva and I. F. Golubev, *Experimental Measurements of Nitrogen Viscosity at Temperatures of 82 to 276.2 K and Pressures of 1 to 506 bar,* Foreign Tech. Div., U. S. Air Force, Report No. FTD-HT-23-1276-71, (1971).
[28]B. Latto and M. W. Saunders, Can. J. Chem. Eng. **50**, 765 (1972).
[29]M. Ikeda, Sasebo Kogyo Koto Senm. Gakko Kenk. Hok. **20**, 73 (1983).
[30]C. Y. Tsui, *Viscosity Measurements for Several Fluorinated Hydrocarbon Vapors at Elevated Pressures and Temperatures,* thesis, Purdue University, 1959.
[31]D. L. Timrot, M. A. Serednitskaya, and S. A. Traktueva, Teploenergetika **16**, 83 (1969).
[32]T. Makita, Rev. Phys. Chem. Jpn. **27**, 16 (1957).
[33]A. G. Clarke and E. B. Smith, J. Chem. Phys. **51**, 4156 (1969).
[34]R. A. Dawe and E. B. Smith, J. Chem. Phys. **52**, 693 (1970).
[35]M. Rigby and E. B. Smith, J. Chem. Soc. Faraday Trans. 1 **62**, 54 (1966).
[36]V. I. Lukin, B. A. Ivakin, and P. E. Suetin, Sov. Phys. Tech. Phys. **28**, 597 (1983).
[37]H. J. M. Hanley and J. F. Ely, J. Phys. Chem. Ref. Data **2**, 735 (1973).
[38]G. C. Maitland and E. B. Smith, J. Chem. Eng. Data **17**, 150 (1972).
[39]N. Matsunaga, T. Hoshino, and A. Nagashima, Int. Gas Turbine Congress, Tokyo 321 (1983).
[40]JSME Data Book, *Thermophysical Properties of Fluids,* JSME (1983).
[41]A. Boushehri, J. Bzowski, J. Kestin, and E. A. Mason, J. Phys. Chem. Ref. Data **16**, 445 (1987).
[42]J. D. Baron, J. G. Roof, and F. W. Wells, J. Chem. Eng. Data **4**, 283 (1959).
[43]G. L. Chierici and A. Paratella, AIChE J. **15**, 786 (1969).
[44]J. T. F. Kao and R. Kobayashi, J. Chem. Phys. **47**, 2836 (1967).
[45]J. P. Schlumpf, F. Lazarre, and P. Viallet, J. Chim. Phys. **72**, 631 (1975).
[46]I. F. Golubev and V. I. Kurin, Teploenergetika **8**, 83 (1974).
[47]J. A. Gracki, G. P. Flynn, and J. Ross, J. Chem. Phys. **51**, 3856 (1969).
[48]E. G. Reynes and G. Thodos, J. Chem. Eng. Data **11**, 137 (1966).

[49]J. Kestin and J. H. Whitelaw, Physica **29**, 335 (1963).
[50]J. F. Ross and G. M. Brown, Industr. Eng. Chem. **49**, 2026 (1957).
[51]G. P. Flynn, R. V. Hanks, N. A. Lemaire, and J. Ross, J. Chem. Phys. **38**, 154 (1963).
[52]K. Goldman, Physica **29**, 499 (1963).
[53]R. A. Makavetskas, V. N. Popov, and N. V. Tsederberg, Teplofiz. Vys. Temp. **1**, 191 (1963).
[54]H. Kobayashi and K. Kurase, Keiryo Kenk. Hokoku **26**, 83 (1977).
[55]S. Foerster, Cryogenics **3**, 176 (1963).
[56]N. S. Rudenko, J. Exp. Theor. Physik **9**, 1078 (1939).
[57]J. P. Boon, J. C. Legros, and G. Thomaes, Physica **33**, 547 (1967).
[58]H. J. M. Hanley, R. D. McCarty, and W. M. Haynes, J. Phys. Chem. Ref. Data **3**, 979 (1974).
[59]C. S. Wang Chang, G. E. Uhlenbeck, and J. de Boer, *Studies in Statistical Mechanics*, edited by J. de Boer and G. E. Uhlenbeck (North-Holland, Amsterdam, 1964), Vol. 2, Part C.
[60]G. C. Maitland, M. Mustafa, and W. A. Wakeham, J. Chem. Soc. Faraday Trans. 1 **79**, 163 (1983).
[61]F. G. Keyes, Trans. ASME **77**, 1395 (1955).
[62]V. P. Slyusar, V. M. Tret'yakov, and N. S. Rudenko, Fiz. Nizk. Temp. **1**, 1159 (1975).
[63]A. A. Clifford, J. Kestin, and W. A. Wakeham, Physica **97A**, 287 (1979).
[64]S. H. P. Chen and S. C. Saxena, High Temp. Science **5**, 206 (1973).
[65]A. A. Westenberg and N. de Haas, Phys. Fluids **5**, 266 (1962).
[66]M. Yorizane, S. Yoshimura, H. Masuoka, and H. Yoshida, Industr. Eng. Chem. Fund. **22**, 454 (1983).
[67]F. G. Keyes and D. J. Sandell, Trans. ASME **72**, 767 (1950).
[68]K. Schaefer and F. W. Reiter, Z. Elektrochemie **61**, 1230 (1957).
[69]H. Geier and K. Schaefer, Allg. Waermetech. **10**, 70 (1961).
[70]W. F. Schottky, Z. Elektrochem. **56**, 889 (1952).
[71]R. C. Reid, J. M. Prausnitz, and Th. K. Sherwood, *The Properties of Gases and Liquids* (McGraw-Hill, New York, 1977).
[72]R. Tufeu and B. Le Neindre, Int. J. Thermophysics **1**, 375 (1980).
[73]H. M. Roder, J. Res. Natl. Bur. Stand. **86**, 457 (1981).
[74]M. J. Assael and W. A. Wakeham, J. Chem. Soc. Faraday. Trans. 1 **77**, 697 (1981).
[75]E. N. Haran, G. C. Maitland, M. Mustafa, and W. A. Wakeham, Ber. Bunsenges. Phys. Chem. **87**, 657 (1983).
[76]H. Ziebland and J. T. A. Burton, Br. J. Appl. Phys. **9**, 52 (1958).
[77]R. L. Nuttal and D. C. Ginnings, J. Res. Natl. Bur. Stand. **58**, 271 (1957).
[78]B. Le Neindre, Int. J. Heat Mass Transfer **15**, 1 (1972).
[79]P. Johannin, J. Res. CNRS **43**, 143 (1958).
[80]E. A. Stolyarov, W. W. Ipatjev, and W. P. Theodorowitsch, Zh. Fiz. Khim. **24**, 166 (1950).
[81]I. F. Golubev and M. V. Kalzsina, Gazov. Prom. **9**, 41 (1964).
[82]F. M. Faubert and G. S. Springer, J. Chem. Phys. **57**, 2333 (1972).
[83]T. J. S. Brain, Int. J. Heat Mass Transfer **10**, 737 (1967).
[84]S. C. Saxena and S. H. P. Chen, Mol. Phys. **29**, 1507 (1975).
[85]R. G. Vines, Trans. ASME **82**, 48 (1960).
[86]E. U. Franck, Z. Elektrochemie **55**, 636 (1951).
[87]A. A. Clifford, P. Gray, A. I. Johns, A. C. Scott, and J. T. R. Watson, J. Chem. Soc. Faraday Trans. 1 **77**, 2679 (1981).
[88]Y. S. Touloukian, P. E. Liley, and S. C. Saxena, *Thermal Conductivity*, TPRC Data Series IFI (Plenum, New York, 1970), Vol. 3.
[89]N. Kh. Zimina and I. A. Rogovaja, VINITI (3241–78) (1978).
[90]N. B. Vargaftik, L. P. Filippov, A. A. Tarzimanov, and E. E. Tozkij, *Thermal Conductivity of Liquids and Gases*, Izd. Standartov, Moscow (1978) (Russ.).
[91]H. Ziebland and K. N. Marsh, Pure Appl. Chem. **53**, 1863 (1981).
[92]R. S. Gamphir and S. C. Saxena, Suppl. Def. Sci. J. **17**, 35 (1967).
[93]K. Mito, D. Hisajima, N. Matsunaga, M. Miyata, and A. Nagashima, in "Proceedings of the Sixth Japan Symposium on Thermophysical Properties," 1985, p. 53.
[94]F. G. Keyes and R. G. Vines, J. Heat Transfer **87**, 177 (1965).
[95]D. Misic and G. Thodos, AIChE J. **11**, 650 (1965).
[96]X.-Y. Zheng, S. Yamamoto, H. Yoshida, H. Masuoka, and M. Yorizane, J. Chem. Eng. Jpn. **17**, 237 (1984).
[97]A. Uhlir Jr., J. Chem. Phys. **20**, 463 (1952).
[98]J. M. Lenoir and E. W. Comings, Chem. Eng. Prog. **47**, 223 (1951).
[99]J. M. Lenoir, W. A. Junk, and E. W. Comings, Chem. Eng. Prog. **49**, 539 (1953).
[100]F. G. Keyes, Trans. ASME **73**, 597 (1951).
[101]E. Borovik, Zh. Eksp. Teor. Fiz. **17**, 328 (1947).
[102]R. Tufeu and B. Le Neindre, Inzh. Fiz. Zh. **36**, 472 (1979).
[103]J. R. Moszynski and B. P. Singh, "Proceedings of the 6th Symposium Thermophysical Properties," ASME, Purdue University 22 (1973).
[104]A. Laesecke, *Viskositaet und Waermeleitfaehigkeit als thermodynamische Zustandsgroessen und ihre Darstellung durch Zustandsgleichungen*, VDI-Fortschr, Ber. Nr. 117, VDI-Verlag Duesseldorf (1986).

Appendix A

```
      FUNCTION DV0203(T)
******************************************************************
*     DILUTE GAS FUNCTION, VISCOSITY OF NITROGEN                 *
*     VALIDITY RANGE   : TRIPLEPOINT - 3000 KELVIN               *
*     INPUT  : TEMPERATURE T (KELVIN)                            *
*     OUTPUT : VISCOSITY DV0203 (MICROPASCAL*SECOND)             *
******************************************************************
      DIMENSION A(0:4)
      DATA A /0.46649,-0.57015,0.19164,-0.03708,0.00241/
      DATA C1,C2,BOLTZ /0.3125E6,2.0442E-49,1.38062E-23/
      DATA EPS,SIG /138.08483E-23,0.36502496E-9/
      OMEGA = 0.
      DO 10 I=0,4
 10   OMEGA = OMEGA + A(I)*ALOG(T*BOLTZ/EPS)**I
      DV0203 = C1*SQRT(C2*T)/(SIG*SIG*EXP(OMEGA))
      RETURN
      END
      FUNCTION DVD203(RO)
******************************************************************
*     EXCESS FUNCTION, VISCOSITY OF NITROGEN                     *
*     VALIDITY RANGE: < 830 KILOGRAM/CUBICMETER                  *
*     INPUT  : DENSITY RO (KILOGRAM/CUBICMETER)                  *
*     OUTPUT : VISCOSITY DVD203 (MICROPASCAL*SECOND)             *
******************************************************************
      DIMENSION C(5)
      DATA C /-20.099970, 3.4376416,
     &        -1.4470051, -.27766561E-01, -.21662362/
      DATA RONORM,TPNORM /314.,14./
      RHO = RO/RONORM
      SUM = C(1)/(RHO-C(2)) + C(1)/C(2)
      DO 10 I=3,5
 10   SUM = SUM + C(I)*RHO**(I-2)
      DVD203 = SUM*TPNORM
      RETURN
      END
```

Table A1. Viscosity (μPa·s) of nitrogen

T (K) \ p (bar)	1.00	10.00	20.00	30.00	40.00	50.00	60.00	70.00	80.00	90.00	100.00
80.00	5.24	133.95	136.16	138.36	140.54	142.72	144.88	147.04	149.18	151.32	153.45
100.00	6.69	73.15	75.51	77.79	80.01	82.17	84.28	86.35	88.39	90.39	92.36
120.00	8.03	8.46	9.34	38.76	42.42	45.38	47.98	50.34	52.54	54.62	56.60
140.00	9.34	9.68	10.20	11.02	12.48	15.51	20.66	25.43	29.07	31.98	34.46
160.00	10.58	10.86	11.25	11.77	12.47	13.41	14.65	16.23	18.11	20.16	22.23
180.00	11.76	12.00	12.32	12.71	13.19	13.78	14.49	15.31	16.26	17.32	18.47
200.00	12.89	13.10	13.37	13.68	14.06	14.50	15.00	15.57	16.20	16.89	17.64
210.00	13.43	13.63	13.88	14.17	14.51	14.90	15.34	15.83	16.38	16.96	17.60
220.00	13.97	14.16	14.39	14.66	14.97	15.32	15.71	16.15	16.62	17.14	17.68
230.00	14.49	14.67	14.89	15.14	15.42	15.74	16.10	16.49	16.91	17.37	17.85
240.00	15.00	15.18	15.38	15.61	15.88	16.17	16.50	16.85	17.24	17.64	18.08
250.00	15.51	15.67	15.86	16.08	16.33	16.60	16.90	17.23	17.58	17.95	18.34
260.00	16.00	16.16	16.34	16.55	16.78	17.04	17.31	17.61	17.93	18.28	18.64
270.00	16.49	16.64	16.81	17.01	17.23	17.47	17.72	18.00	18.30	18.62	18.95
280.00	16.96	17.11	17.28	17.46	17.67	17.89	18.14	18.40	18.67	18.97	19.27
290.00	17.44	17.58	17.74	17.91	18.11	18.32	18.55	18.79	19.05	19.32	19.61
300.00	17.90	18.03	18.19	18.36	18.54	18.74	18.96	19.19	19.43	19.69	19.96
310.00	18.36	18.49	18.63	18.79	18.97	19.16	19.37	19.58	19.81	20.05	20.31
320.00	18.80	18.93	19.07	19.23	19.40	19.58	19.77	19.98	20.20	20.42	20.66
330.00	19.25	19.37	19.51	19.65	19.82	19.99	20.17	20.37	20.58	20.79	21.02
340.00	19.69	19.80	19.93	20.08	20.23	20.40	20.58	20.76	20.96	21.16	21.38
350.00	20.12	20.23	20.36	20.50	20.64	20.80	20.97	21.15	21.34	21.53	21.74
360.00	20.54	20.65	20.78	20.91	21.05	21.21	21.37	21.54	21.72	21.90	22.10
370.00	20.96	21.07	21.19	21.32	21.46	21.60	21.76	21.92	22.09	22.27	22.46
380.00	21.38	21.48	21.60	21.72	21.86	22.00	22.15	22.30	22.47	22.64	22.82
390.00	21.79	21.89	22.00	22.12	22.25	22.39	22.53	22.68	22.84	23.01	23.18
400.00	22.19	22.29	22.40	22.52	22.64	22.77	22.91	23.06	23.21	23.37	23.54
420.00	22.99	23.09	23.19	23.30	23.42	23.54	23.67	23.81	23.95	24.09	24.25
440.00	23.77	23.86	23.96	24.06	24.17	24.29	24.41	24.54	24.67	24.81	24.95
460.00	24.54	24.62	24.72	24.81	24.92	25.03	25.14	25.26	25.39	25.52	25.65
480.00	25.29	25.37	25.46	25.55	25.65	25.75	25.86	25.98	26.09	26.21	26.34
500.00	26.02	26.10	26.19	26.28	26.37	26.47	26.57	26.68	26.79	26.90	27.02
520.00	26.75	26.82	26.90	26.99	27.08	27.17	27.27	27.37	27.48	27.59	27.70
540.00	27.46	27.53	27.61	27.69	27.78	27.87	27.96	28.06	28.16	28.26	28.37
560.00	28.16	28.23	28.30	28.38	28.46	28.55	28.64	28.73	28.83	28.92	29.03
580.00	28.85	28.92	28.99	29.06	29.14	29.22	29.31	29.40	29.49	29.58	29.68
600.00	29.53	29.59	29.66	29.74	29.81	29.89	29.97	30.06	30.14	30.23	30.32
650.00	31.19	31.25	31.31	31.38	31.44	31.52	31.59	31.67	31.74	31.82	31.91
700.00	32.79	32.85	32.90	32.96	33.03	33.09	33.16	33.23	33.30	33.38	33.45
750.00	34.35	34.40	34.45	34.51	34.57	34.63	34.69	34.75	34.82	34.89	34.96
800.00	35.86	35.91	35.96	36.01	36.07	36.12	36.18	36.24	36.30	36.36	36.43
850.00	37.34	37.39	37.43	37.48	37.53	37.59	37.64	37.69	37.75	37.81	37.87
900.00	38.79	38.83	38.87	38.92	38.97	39.02	39.07	39.12	39.17	39.22	39.28
950.00	40.20	40.24	40.28	40.32	40.37	40.42	40.46	40.51	40.56	40.61	40.66
1000.00	41.58	41.62	41.66	41.70	41.75	41.79	41.83	41.88	41.93	41.97	42.02
1050.00	42.94	42.98	43.02	43.06	43.10	43.14	43.18	43.22	43.27	43.31	43.36
1100.00	44.28	44.31	44.35	44.39	44.42	44.46	44.50	44.54	44.59	44.63	44.67

Table A1. Viscosity (μPa·s) of nitrogen -- Continued

T (K)	p (bar) 125.00	150.00	175.00	200.00	225.00	250.00	275.00	300.00	350.00	400.00	450.00
80.00	158.76	164.04	------	------	------	------	------	------	------	------	------
100.00	97.20	101.92	106.56	111.13	115.65	120.13	124.58	129.02	137.86	146.70	155.58
120.00	61.26	65.61	69.76	73.75	77.64	81.43	85.16	88.84	96.10	103.26	110.37
140.00	39.59	43.93	47.82	51.45	54.89	58.20	61.41	64.54	70.64	76.60	82.46
160.00	27.02	31.17	34.81	38.12	41.20	44.11	46.90	49.60	54.81	59.85	64.78
180.00	21.56	24.68	27.66	30.46	33.11	35.62	38.03	40.36	44.83	49.14	53.33
200.00	19.69	21.90	24.15	26.37	28.54	30.64	32.67	34.66	38.48	42.18	45.79
210.00	19.34	21.23	23.19	25.16	27.10	29.01	30.87	32.70	36.24	39.67	43.02
220.00	19.19	20.83	22.56	24.31	26.06	27.79	29.49	31.17	34.44	37.63	40.74
230.00	19.18	20.63	22.16	23.72	25.30	26.88	28.44	29.98	33.01	35.97	38.88
240.00	19.26	20.55	21.92	23.33	24.77	26.20	27.64	29.06	31.87	34.62	37.34
250.00	19.41	20.58	21.81	23.09	24.40	25.72	27.04	28.35	30.96	33.53	36.07
260.00	19.61	20.67	21.80	22.96	24.16	25.38	26.59	27.81	30.24	32.65	35.03
270.00	19.84	20.81	21.85	22.92	24.03	25.15	26.28	27.41	29.68	31.94	34.18
280.00	20.10	21.00	21.95	22.95	23.97	25.01	26.06	27.12	29.24	31.36	33.47
290.00	20.38	21.21	22.10	23.02	23.97	24.94	25.93	26.92	28.91	30.91	32.90
300.00	20.68	21.45	22.28	23.14	24.03	24.94	25.86	26.79	28.67	30.55	32.43
310.00	20.98	21.71	22.48	23.29	24.12	24.98	25.84	26.72	28.49	30.27	32.06
320.00	21.30	21.98	22.71	23.47	24.25	25.06	25.87	26.70	28.38	30.07	31.76
330.00	21.62	22.27	22.95	23.67	24.41	25.17	25.94	26.73	28.31	29.92	31.53
340.00	21.95	22.56	23.21	23.89	24.59	25.31	26.04	26.78	28.29	29.82	31.36
350.00	22.28	22.86	23.48	24.12	24.79	25.47	26.17	26.87	28.31	29.77	31.23
360.00	22.62	23.17	23.76	24.37	25.00	25.65	26.31	26.99	28.36	29.75	31.15
370.00	22.95	23.48	24.04	24.62	25.23	25.85	26.48	27.12	28.43	29.76	31.11
380.00	23.29	23.80	24.33	24.89	25.46	26.05	26.66	27.28	28.53	29.81	31.10
390.00	23.63	24.11	24.62	25.16	25.71	26.28	26.86	27.45	28.65	29.87	31.11
400.00	23.97	24.43	24.92	25.43	25.96	26.51	27.06	27.63	28.78	29.96	31.16
420.00	24.65	25.08	25.53	26.00	26.49	26.99	27.51	28.03	29.10	30.19	31.30
440.00	25.33	25.73	26.15	26.58	27.04	27.50	27.98	28.47	29.46	30.48	31.52
460.00	26.00	26.37	26.76	27.17	27.60	28.03	28.48	28.93	29.86	30.81	31.78
480.00	26.67	27.02	27.39	27.77	28.17	28.57	28.99	29.42	30.29	31.18	32.09
500.00	27.33	27.66	28.01	28.37	28.74	29.12	29.52	29.92	30.74	31.58	32.44
520.00	27.99	28.30	28.63	28.97	29.32	29.68	30.05	30.43	31.21	32.00	32.81
540.00	28.64	28.94	29.25	29.57	29.90	30.24	30.59	30.95	31.69	32.44	33.21
560.00	29.29	29.57	29.86	30.17	30.48	30.81	31.14	31.48	32.18	32.89	33.63
580.00	29.93	30.20	30.48	30.77	31.07	31.37	31.69	32.01	32.68	33.36	34.06
600.00	30.56	30.82	31.08	31.36	31.65	31.94	32.24	32.55	33.18	33.83	34.50
650.00	32.12	32.35	32.59	32.84	33.09	33.35	33.62	33.90	34.47	35.05	35.65
700.00	33.65	33.85	34.07	34.29	34.52	34.76	35.00	35.25	35.76	36.29	36.83
750.00	35.14	35.32	35.52	35.72	35.93	36.15	36.37	36.60	37.06	37.55	38.04
800.00	36.59	36.77	36.95	37.13	37.33	37.52	37.73	37.94	38.36	38.80	39.26
850.00	38.02	38.18	38.35	38.52	38.70	38.88	39.07	39.26	39.65	40.06	40.48
900.00	39.42	39.57	39.72	39.88	40.05	40.22	40.39	40.57	40.94	41.32	41.70
950.00	40.80	40.93	41.08	41.23	41.38	41.54	41.70	41.87	42.21	42.56	42.93
1000.00	42.15	42.28	42.41	42.55	42.70	42.84	43.00	43.15	43.47	43.80	44.14
1050.00	43.47	43.60	43.72	43.86	43.99	44.13	44.27	44.42	44.72	45.03	45.35
1100.00	44.78	44.90	45.02	45.14	45.27	45.40	45.54	45.67	45.96	46.25	46.55

Table A1. Viscosity (μPa·s) of nitrogen -- Continued

T (K) \ p (bar)	500.00	550.00	600.00	650.00	700.00	750.00	800.00	850.00	900.00	950.00	1000.00
80.00	------	------	------	------	------	------	------	------	------	------	------
100.00	164.52	------	------	------	------	------	------	------	------	------	------
120.00	117.48	124.61	131.79	139.04	146.35	153.75	161.26	------	------	------	------
140.00	88.27	94.07	99.86	105.68	111.54	117.43	123.39	129.42	135.53	141.72	148.01
160.00	69.65	74.48	79.29	84.10	88.93	93.79	98.67	103.61	108.58	113.62	118.72
180.00	57.47	61.56	65.63	69.70	73.77	77.86	81.96	86.10	90.27	94.48	98.74
200.00	49.34	52.85	56.34	59.82	63.31	66.81	70.32	73.86	77.42	81.02	84.65
210.00	46.32	49.58	52.83	56.07	59.31	62.57	65.83	69.12	72.43	75.77	79.15
220.00	43.82	46.86	49.89	52.91	55.94	58.97	62.02	65.09	68.18	71.29	74.43
230.00	41.75	44.59	47.42	50.25	53.08	55.92	58.77	61.64	64.53	67.44	70.38
240.00	40.03	42.69	45.34	47.99	50.65	53.31	55.98	58.67	61.38	64.11	66.87
250.00	38.59	41.09	43.58	46.07	48.57	51.07	53.59	56.11	58.66	61.23	63.82
260.00	37.40	39.75	42.10	44.44	46.79	49.15	51.52	53.90	56.30	58.72	61.16
270.00	36.40	38.62	40.83	43.05	45.26	47.49	49.73	51.98	54.25	56.54	58.84
280.00	35.57	37.67	39.76	41.85	43.95	46.06	48.18	50.31	52.45	54.62	56.81
290.00	34.88	36.87	38.85	40.83	42.82	44.82	46.83	48.85	50.89	52.94	55.01
300.00	34.31	36.19	38.07	39.96	41.85	43.75	45.66	47.58	49.51	51.46	53.43
310.00	33.84	35.63	37.42	39.21	41.01	42.81	44.63	46.46	48.31	50.16	52.04
320.00	33.46	35.16	36.86	38.57	40.29	42.01	43.74	45.49	47.24	49.02	50.80
330.00	33.15	34.77	36.40	38.03	39.66	41.31	42.96	44.63	46.31	48.00	49.71
340.00	32.90	34.45	36.00	37.56	39.13	40.70	42.29	43.88	45.49	47.11	48.74
350.00	32.71	34.19	35.68	37.17	38.67	40.18	41.70	43.22	44.76	46.31	47.88
360.00	32.57	33.99	35.41	36.84	38.28	39.73	41.18	42.65	44.13	45.61	47.12
370.00	32.47	33.83	35.20	36.57	37.95	39.34	40.74	42.15	43.57	45.00	46.44
380.00	32.40	33.71	35.02	36.35	37.67	39.01	40.36	41.71	43.07	44.45	45.84
390.00	32.37	33.62	34.89	36.16	37.44	38.73	40.03	41.33	42.64	43.97	45.31
400.00	32.36	33.57	34.79	36.02	37.25	38.49	39.74	41.00	42.27	43.55	44.83
420.00	32.42	33.55	34.69	35.83	36.98	38.14	39.30	40.48	41.66	42.85	44.05
440.00	32.56	33.62	34.68	35.75	36.83	37.91	39.00	40.10	41.21	42.32	43.45
460.00	32.76	33.75	34.75	35.76	36.77	37.79	38.82	39.85	40.89	41.94	42.99
480.00	33.02	33.95	34.89	35.84	36.79	37.75	38.72	39.69	40.68	41.66	42.66
500.00	33.31	34.19	35.08	35.98	36.88	37.79	38.70	39.62	40.55	41.49	42.43
520.00	33.64	34.47	35.31	36.16	37.02	37.88	38.75	39.62	40.50	41.39	42.28
540.00	33.99	34.78	35.59	36.39	37.21	38.02	38.85	39.68	40.52	41.36	42.21
560.00	34.37	35.12	35.89	36.65	37.43	38.21	39.00	39.79	40.58	41.39	42.19
580.00	34.77	35.48	36.21	36.94	37.68	38.43	39.18	39.94	40.70	41.46	42.23
600.00	35.18	35.86	36.56	37.26	37.97	38.68	39.40	40.12	40.85	41.58	42.32
650.00	36.25	36.87	37.50	38.13	38.77	39.41	40.06	40.71	41.36	42.03	42.69
700.00	37.38	37.94	38.51	39.08	39.66	40.25	40.84	41.43	42.03	42.63	43.24
750.00	38.54	39.05	39.57	40.10	40.63	41.17	41.71	42.25	42.80	43.35	43.91
800.00	39.72	40.19	40.67	41.15	41.64	42.14	42.64	43.14	43.64	44.15	44.67
850.00	40.91	41.35	41.79	42.24	42.69	43.15	43.61	44.08	44.55	45.02	45.50
900.00	42.10	42.51	42.92	43.34	43.76	44.19	44.62	45.05	45.49	45.93	46.38
950.00	43.30	43.67	44.06	44.45	44.85	45.24	45.65	46.06	46.47	46.88	47.29
1000.00	44.49	44.84	45.20	45.57	45.94	46.32	46.69	47.08	47.46	47.85	48.24
1050.00	45.68	46.01	46.35	46.69	47.04	47.40	47.75	48.11	48.48	48.84	49.21
1100.00	46.86	47.17	47.49	47.82	48.15	48.48	48.82	49.16	49.50	49.85	50.20

Table A2. Viscosity of nitrogen, saturation line

p (bar)	T (K)	(μPa·s)
.38976	70.0	4.42
.76803	75.0	4.81
.76803	75.0	153.18
1.3804	80.0	5.26
1.3804	80.0	132.04
2.3048	85.0	5.68
2.3048	85.0	113.81
3.6246	90.0	6.11
3.6246	90.0	98.09
5.4277	95.0	6.58
5.4277	95.0	84.48
7.8047	100.0	7.08
7.8047	100.0	72.62
10.850	105.0	7.64
10.850	105.0	62.21
14.664	110.0	8.31
14.664	110.0	52.97
19.360	115.0	9.16
19.360	115.0	44.55
25.082	120.0	10.40
25.082	120.0	36.40
32.067	125.0	13.27
32.067	125.0	26.32
34.000	126.2	18.91

Appendix B

```
      FUNCTION TC0203(T)
*****************************************************************
*     DILUTE GAS FUNCTION, THERMAL CONDUCTIVITY OF NITROGEN     *
*     VALIDITY RANGE    : TRIPLEPOINT - 3000 KELVIN             *
*     INPUT  : TEMPERATURE T (KELVIN)                           *
*     OUTPUT : THERMAL CONDUCT. TC0203 (MILLIWATT/METER*KELVIN) *
*****************************************************************
      DIMENSION X(2)
      DATA CK,CN /1.38062E-23, 6.02213E26/
      DATA AMOL /28.013/
      DATA X /0.95185202, 1.0205422/
      CVINT = CVIDEAL(T)*1000./CN
      FAC = DV0203(T)*CK*CN/(AMOL*1000.)
      TCTRA = 2.5*(1.5 - X(1))
      TCINT = X(2)*(CVINT/CK +X(1))
      TC0203 = FAC*(TCTRA + TCINT)
      RETURN
      END
      FUNCTION TCD203(RO)
*****************************************************************
*     EXCESS FUNCTION, THERMAL CONDUCTIVITY OF NITROGEN         *
*     VALIDITY RANGE: < 1090 KILOGRAM/CUBICMETER                *
*     INPUT  : DENSITY RO (KILOGRAM/CUBICMETER)                 *
*     OUTPUT : THERMAL CONDUCT. TCD203 (MILLIWATT/METER*KELVIN) *
*****************************************************************
      DIMENSION COEFF(4)
      DATA COEFF /3.3373542, 0.37098251, 0.89913456, 0.16972505/
      DATA RONORM,TPNORM /314., 4.17/
      RHO = RO/RONORM
      SUM = 0.
      DO 10 I=1,4
 10   SUM = SUM + COEFF(I)*RHO**I
      TCD203 = SUM*TPNORM
      RETURN
      END
      FUNCTION CVIDEAL(T)
*****************************************************************
*     SPECIF. VOLUM. HEAT CAPACITY OF NITROGEN (DILUTE GAS)     *
*     INPUT:  TEMPERATURE T (KELVIN)                            *
*     OUTPUT: CAPACITY CVIDEAL (JOULE/MOLE*KELVIN)              *
*****************************************************************
      DIMENSION F(9)
      DATA R /8.31434/
      DATA F /-0.837079888737E3,   0.379147114487E2,
     &        -0.601737844275,     0.350418363823E1,
     &        -0.874955653028E-5,  0.148968607239E-7,
     &        -0.256370354277E-11, 0.100773735767E1,
     &         0.335340610E4/
      SUM1 = 0.
      DO 10 I=1,7
 10   SUM1 = SUM1 + F(I)*T**(I-4)
      U = F(9)/T
      EU1 = EXP(U) - 1
      SUM2 = (F(8)*U*U*(EU1 + 1))/(EU1*EU1)
      CVIDEAL = R*(SUM1 + SUM2 - 1.)
      RETURN
      END
```

Table B1. Thermal conductivity (mW/m·K) of nitrogen

T (K) \ p (bar)	1.00	10.00	20.00	30.00	40.00	50.00	60.00	70.00	80.00	90.00	100.00
70.00	163.19	163.94	164.76	165.58	166.38	167.17	167.95	168.72	169.47	170.22	170.96
80.00	7.73	144.18	145.32	146.44	147.54	148.61	149.67	150.70	151.72	152.72	153.70
100.00	9.81	104.03	106.12	108.09	109.96	111.74	113.45	115.08	116.66	118.18	119.66
120.00	11.67	13.11	15.35	65.72	70.79	74.71	78.00	80.90	83.52	85.92	88.15
140.00	13.57	14.73	16.17	18.10	21.06	26.72	36.04	44.46	50.65	55.40	59.29
160.00	15.37	16.36	17.48	18.79	20.35	22.26	24.63	27.57	31.00	34.70	38.42
180.00	17.08	17.95	18.89	19.92	21.06	22.34	23.77	25.37	27.16	29.12	31.22
200.00	18.72	19.49	20.30	21.17	22.10	23.10	24.17	25.32	26.55	27.86	29.25
210.00	19.51	20.24	21.00	21.81	22.67	23.57	24.53	25.55	26.63	27.76	28.96
220.00	20.29	20.98	21.70	22.46	23.25	24.08	24.96	25.87	26.83	27.84	28.89
230.00	21.05	21.71	22.39	23.10	23.84	24.62	25.42	26.26	27.13	28.04	28.98
240.00	21.79	22.42	23.08	23.75	24.44	25.17	25.91	26.69	27.49	28.31	29.17
250.00	22.52	23.13	23.75	24.39	25.05	25.73	26.42	27.14	27.88	28.65	29.43
260.00	23.24	23.82	24.42	25.03	25.65	26.29	26.95	27.62	28.31	29.02	29.75
270.00	23.95	24.51	25.08	25.66	26.25	26.86	27.48	28.12	28.77	29.43	30.11
280.00	24.65	25.19	25.73	26.29	26.86	27.43	28.02	28.62	29.24	29.86	30.50
290.00	25.33	25.85	26.38	26.91	27.46	28.01	28.57	29.14	29.72	30.31	30.91
300.00	26.01	26.51	27.02	27.53	28.05	28.58	29.12	29.66	30.21	30.77	31.34
310.00	26.68	27.16	27.65	28.14	28.65	29.15	29.66	30.18	30.71	31.24	31.78
320.00	27.33	27.80	28.28	28.75	29.24	29.72	30.21	30.71	31.22	31.73	32.24
330.00	27.98	28.44	28.90	29.36	29.82	30.29	30.77	31.24	31.73	32.21	32.71
340.00	28.63	29.07	29.51	29.96	30.41	30.86	31.32	31.78	32.24	32.71	33.18
350.00	29.26	29.69	30.12	30.55	30.99	31.42	31.87	32.31	32.76	33.21	33.66
360.00	29.89	30.31	30.72	31.14	31.56	31.99	32.41	32.84	33.27	33.71	34.15
370.00	30.51	30.92	31.32	31.73	32.14	32.55	32.96	33.38	33.79	34.21	34.63
380.00	31.13	31.53	31.92	32.31	32.71	33.11	33.51	33.91	34.31	34.72	35.13
390.00	31.74	32.13	32.51	32.90	33.28	33.67	34.06	34.45	34.84	35.23	35.62
400.00	32.35	32.73	33.10	33.47	33.85	34.22	34.60	34.98	35.36	35.74	36.12
420.00	33.56	33.91	34.27	34.62	34.98	35.33	35.69	36.05	36.41	36.77	37.13
440.00	34.74	35.08	35.42	35.76	36.10	36.44	36.78	37.12	37.46	37.80	38.14
460.00	35.92	36.25	36.57	36.89	37.22	37.54	37.86	38.18	38.51	38.83	39.15
480.00	37.09	37.40	37.71	38.02	38.33	38.64	38.95	39.25	39.56	39.87	40.18
500.00	38.25	38.55	38.85	39.14	39.44	39.73	40.03	40.32	40.62	40.91	41.21
520.00	39.40	39.69	39.98	40.26	40.55	40.83	41.11	41.40	41.68	41.96	42.24
540.00	40.55	40.83	41.10	41.38	41.65	41.92	42.20	42.47	42.74	43.01	43.28
560.00	41.70	41.96	42.23	42.49	42.75	43.02	43.28	43.54	43.80	44.06	44.32
580.00	42.83	43.09	43.35	43.60	43.86	44.11	44.36	44.61	44.87	45.12	45.37
600.00	43.97	44.22	44.47	44.71	44.96	45.20	45.45	45.69	45.93	46.17	46.42
650.00	46.79	47.02	47.25	47.48	47.71	47.93	48.16	48.38	48.60	48.83	49.05
700.00	49.60	49.81	50.02	50.23	50.44	50.65	50.86	51.07	51.28	51.48	51.69
750.00	52.38	52.58	52.77	52.97	53.17	53.36	53.56	53.75	53.94	54.14	54.33
800.00	55.13	55.32	55.50	55.69	55.87	56.06	56.24	56.42	56.60	56.78	56.96
850.00	57.86	58.03	58.21	58.38	58.56	58.73	58.90	59.07	59.24	59.41	59.58
900.00	60.55	60.72	60.88	61.05	61.21	61.37	61.54	61.70	61.86	62.02	62.18
950.00	63.21	63.37	63.53	63.68	63.84	63.99	64.15	64.30	64.45	64.60	64.75
1000.00	65.84	65.99	66.14	66.29	66.43	66.58	66.73	66.87	67.02	67.16	67.30
1050.00	68.43	68.57	68.71	68.85	68.99	69.13	69.27	69.41	69.55	69.69	69.83
1100.00	70.98	71.12	71.26	71.39	71.52	71.66	71.79	71.92	72.05	72.19	72.32

Table B1. Thermal conductivity (mW/m.K) of nitrogen -- Continued

T (K) \ p (bar)	125.00	150.00	175.00	200.00	225.00	250.00	275.00	300.00	350.00	400.00	450.00
70.00	172.78	174.53	176.24	177.91	179.53	181.11	182.65	184.15	187.05	189.83	192.49
80.00	156.09	158.39	160.60	162.75	164.82	166.83	168.79	170.69	174.34	177.81	181.13
100.00	123.15	126.42	129.50	132.42	135.21	137.87	140.43	142.89	147.57	151.97	156.13
120.00	93.16	97.61	101.63	105.33	108.77	112.00	115.06	117.96	123.38	128.40	133.08
140.00	66.93	72.96	78.06	82.56	86.63	90.37	93.85	97.12	103.13	108.61	113.67
160.00	46.88	53.87	59.72	64.77	69.25	73.32	77.06	80.54	86.89	92.63	97.89
180.00	36.83	42.42	47.66	52.45	56.82	60.84	64.57	68.05	74.41	80.15	85.43
200.00	33.02	37.04	41.10	45.06	48.86	52.47	55.89	59.14	65.18	70.70	75.82
210.00	32.17	35.62	39.17	42.72	46.18	49.52	52.74	55.82	61.60	66.94	71.92
220.00	31.70	34.71	37.84	41.00	44.14	47.22	50.21	53.10	58.60	63.73	68.55
230.00	31.47	34.14	36.92	39.76	42.61	45.43	48.20	50.91	56.10	61.01	65.64
240.00	31.42	33.81	36.31	38.87	41.47	44.06	46.62	49.14	54.03	58.70	63.14
250.00	31.48	33.66	35.92	38.26	40.63	43.01	45.38	47.73	52.32	56.75	60.99
260.00	31.64	33.63	35.71	37.84	40.02	42.21	44.41	46.61	50.92	55.11	59.16
270.00	31.86	33.70	35.62	37.58	39.60	41.63	43.67	45.72	49.77	53.74	57.60
280.00	32.14	33.85	35.62	37.45	39.32	41.21	43.12	45.03	48.84	52.60	56.27
290.00	32.45	34.05	35.71	37.41	39.15	40.92	42.70	44.50	48.09	51.65	55.14
300.00	32.80	34.30	35.86	37.45	39.08	40.74	42.42	44.10	47.49	50.86	54.20
310.00	33.17	34.59	36.06	37.56	39.09	40.65	42.23	43.82	47.02	50.22	53.40
320.00	33.56	34.91	36.29	37.71	39.16	40.63	42.12	43.63	46.66	49.70	52.73
330.00	33.96	35.25	36.57	37.91	39.28	40.68	42.09	43.52	46.39	49.29	52.19
340.00	34.38	35.61	36.86	38.14	39.45	40.77	42.11	43.47	46.21	48.97	51.74
350.00	34.81	35.99	37.19	38.41	39.65	40.91	42.19	43.48	46.09	48.73	51.38
360.00	35.25	36.38	37.53	38.70	39.88	41.09	42.31	43.54	46.04	48.56	51.09
370.00	35.70	36.79	37.89	39.01	40.14	41.30	42.46	43.64	46.03	48.45	50.88
380.00	36.16	37.20	38.26	39.34	40.43	41.53	42.65	43.78	46.07	48.39	50.73
390.00	36.62	37.63	38.65	39.68	40.73	41.79	42.87	43.95	46.15	48.38	50.63
400.00	37.08	38.06	39.04	40.04	41.05	42.08	43.11	44.15	46.27	48.41	50.57
420.00	38.03	38.94	39.87	40.80	41.74	42.69	43.66	44.63	46.59	48.58	50.60
440.00	38.99	39.85	40.72	41.60	42.48	43.37	44.27	45.18	47.01	48.87	50.76
460.00	39.97	40.78	41.60	42.43	43.26	44.10	44.94	45.80	47.52	49.26	51.03
480.00	40.95	41.73	42.50	43.29	44.07	44.87	45.66	46.47	48.09	49.74	51.40
500.00	41.94	42.68	43.42	44.17	44.92	45.67	46.42	47.18	48.72	50.27	51.85
520.00	42.95	43.65	44.36	45.07	45.78	46.50	47.22	47.94	49.40	50.87	52.36
540.00	43.96	44.63	45.31	45.99	46.67	47.35	48.04	48.72	50.11	51.52	52.93
560.00	44.97	45.62	46.27	46.92	47.57	48.22	48.88	49.54	50.86	52.20	53.55
580.00	45.99	46.62	47.24	47.87	48.49	49.12	49.75	50.38	51.64	52.92	54.21
600.00	47.02	47.62	48.22	48.82	49.42	50.03	50.63	51.23	52.45	53.68	54.91
650.00	49.60	50.15	50.71	51.26	51.80	52.35	52.90	53.46	54.56	55.67	56.79
700.00	52.20	52.71	53.22	53.73	54.24	54.74	55.25	55.75	56.77	57.79	58.81
750.00	54.81	55.28	55.76	56.23	56.70	57.17	57.64	58.11	59.05	59.99	60.93
800.00	57.41	57.85	58.30	58.74	59.18	59.62	60.05	60.49	61.37	62.24	63.12
850.00	60.00	60.42	60.84	61.25	61.66	62.08	62.49	62.90	63.72	64.54	65.36
900.00	62.58	62.97	63.37	63.76	64.15	64.53	64.92	65.31	66.08	66.85	67.62
950.00	65.13	65.51	65.88	66.25	66.62	66.99	67.35	67.72	68.45	69.17	69.90
1000.00	67.66	68.02	68.37	68.72	69.08	69.42	69.77	70.12	70.81	71.50	72.19
1050.00	70.17	70.51	70.84	71.18	71.51	71.85	72.18	72.51	73.16	73.82	74.48
1100.00	72.64	72.97	73.29	73.61	73.93	74.25	74.56	74.88	75.51	76.13	76.76

Table B1. Thermal conductivity (mW/m·K) of nitrogen -- Continued

T (K) \ p (bar)	500.00	550.00	600.00	650.00	700.00	750.00	800.00	850.00	900.00	950.00	1000.00
70.00	195.04	197.50	199.86	202.14	204.35	206.48	208.53	210.53	212.46	214.34	216.16
80.00	184.30	187.33	190.25	193.06	195.76	198.37	200.89	203.33	205.69	207.98	210.19
100.00	160.09	163.87	167.50	170.98	174.33	177.58	180.71	183.75	186.70	189.56	192.34
120.00	137.49	141.67	145.66	149.47	153.13	156.66	160.07	163.38	166.58	169.69	172.72
140.00	118.39	122.83	127.04	131.05	134.89	138.57	142.11	145.54	148.86	152.08	155.21
160.00	102.78	107.37	111.70	115.81	119.73	123.49	127.10	130.59	133.96	137.22	140.40
180.00	90.33	94.92	99.26	103.39	107.32	111.09	114.71	118.20	121.57	124.84	128.01
200.00	80.58	85.07	89.33	93.37	97.24	100.95	104.52	107.97	111.31	114.54	117.68
210.00	76.58	80.98	85.16	89.14	92.96	96.62	100.15	103.56	106.86	110.06	113.17
220.00	73.08	77.38	81.46	85.37	89.12	92.72	96.20	99.56	102.82	105.98	109.06
230.00	70.03	74.20	78.19	82.01	85.67	89.21	92.63	95.94	99.15	102.26	105.30
240.00	67.37	71.41	75.29	79.01	82.60	86.06	89.41	92.65	95.81	98.88	101.87
250.00	65.06	68.97	72.73	76.35	79.84	83.22	86.50	89.68	92.78	95.79	98.73
260.00	63.07	66.83	70.47	73.98	77.38	80.68	83.88	86.99	90.03	92.98	95.86
270.00	61.34	64.96	68.47	71.88	75.18	78.39	81.51	84.55	87.52	90.42	93.24
280.00	59.85	63.33	66.72	70.01	73.22	76.34	79.38	82.35	85.25	88.08	90.85
290.00	58.57	61.92	65.18	68.36	71.47	74.50	77.46	80.35	83.18	85.95	88.67
300.00	57.47	60.69	63.83	66.90	69.91	72.85	75.73	78.55	81.31	84.01	86.67
310.00	56.53	59.62	62.65	65.61	68.53	71.38	74.18	76.92	79.61	82.25	84.84
320.00	55.73	58.69	61.61	64.48	67.29	70.06	72.78	75.44	78.07	80.65	83.17
330.00	55.06	57.90	60.71	63.48	66.20	68.88	71.52	74.11	76.67	79.18	81.66
340.00	54.49	57.22	59.93	62.60	65.24	67.83	70.39	72.91	75.40	77.85	80.26
350.00	54.02	56.64	59.25	61.83	64.38	66.90	69.38	71.83	74.25	76.64	79.00
360.00	53.63	56.16	58.67	61.16	63.63	66.07	68.48	70.86	73.22	75.54	77.84
370.00	53.32	55.75	58.17	60.58	62.97	65.33	67.68	69.99	72.28	74.55	76.79
380.00	53.07	55.42	57.75	60.08	62.39	64.68	66.96	69.21	71.44	73.65	75.83
390.00	52.88	55.14	57.40	59.65	61.89	64.11	66.32	68.51	70.68	72.83	74.97
400.00	52.75	54.93	57.11	59.29	61.46	63.62	65.76	67.89	70.01	72.10	74.18
420.00	52.62	54.66	56.70	58.74	60.78	62.82	64.84	66.86	68.86	70.85	72.83
440.00	52.65	54.56	56.48	58.40	60.32	62.24	64.15	66.06	67.96	69.85	71.74
460.00	52.81	54.61	56.41	58.22	60.03	61.85	63.66	65.47	67.28	69.08	70.87
480.00	53.08	54.77	56.47	58.18	59.90	61.62	63.33	65.05	66.77	68.49	70.20
500.00	53.43	55.03	56.64	58.26	59.89	61.52	63.15	64.79	66.43	68.06	69.69
520.00	53.86	55.38	56.91	58.45	59.99	61.54	63.10	64.66	66.22	67.78	69.34
540.00	54.36	55.80	57.26	58.72	60.19	61.67	63.15	64.64	66.13	67.62	69.11
560.00	54.92	56.29	57.68	59.07	60.47	61.88	63.30	64.72	66.15	67.57	69.00
580.00	55.52	56.83	58.15	59.49	60.83	62.17	63.53	64.89	66.25	67.62	68.99
600.00	56.16	57.42	58.68	59.96	61.24	62.53	63.83	65.13	66.44	67.76	69.07
650.00	57.92	59.05	60.20	61.35	62.51	63.68	64.85	66.03	67.21	68.41	69.60
700.00	59.84	60.88	61.92	62.97	64.03	65.09	66.16	67.24	68.32	69.41	70.50
750.00	61.88	62.83	63.79	64.76	65.73	66.71	67.69	68.68	69.67	70.67	71.68
800.00	64.00	64.89	65.77	66.67	67.57	68.47	69.38	70.30	71.22	72.14	73.07
850.00	66.18	67.00	67.83	68.66	69.50	70.34	71.19	72.04	72.89	73.76	74.62
900.00	68.39	69.17	69.94	70.72	71.51	72.29	73.08	73.88	74.68	75.48	76.29
950.00	70.63	71.36	72.09	72.82	73.56	74.30	75.04	75.79	76.54	77.29	78.05
1000.00	72.88	73.57	74.26	74.95	75.65	76.34	77.05	77.75	78.46	79.17	79.88
1050.00	75.13	75.78	76.44	77.10	77.76	78.42	79.08	79.75	80.41	81.09	81.76
1100.00	77.38	78.00	78.62	79.25	79.88	80.50	81.13	81.77	82.40	83.04	83.68

Table B2. Thermal conductivity of nitrogen, saturation line

p (bar)	T (K)	(mW/m·K)
.38976	70.0	6.42
.38976	70.0	163.14
.76803	75.0	6.98
.76803	75.0	153.20
1.3804	80.0	7.80
1.3804	80.0	143.17
2.3048	85.0	8.51
2.3048	85.0	133.17
3.6246	90.0	9.29
3.6246	90.0	123.23
5.4277	95.0	10.14
5.4277	95.0	113.37
7.8047	100.0	11.10
7.8047	100.0	103.55
10.850	105.0	12.21
10.850	105.0	93.73
14.664	110.0	13.53
14.664	110.0	83.82
19.360	115.0	15.22
19.360	115.0	73.57
25.082	120.0	17.64
25.082	120.0	62.30
32.067	125.0	22.98
32.067	125.0	46.24
34.000	126.2	33.20

Appendix C

Table C1. Transport equation of state (TEOS), viscosity of nitrogen

critical temperature	=	126.2 K
critical pressure	=	34.0 bar
triplepoint temperature	=	63.1 K
molecular weight	=	28.013 kg/kmol
crit. viscosity factor	=	14.058 μPa·s

TEOS coefficients :

a(1)	=	-5.231071901886
a(2)	=	-14.50617603760
a(3)	=	67.81766195964
a(4)	=	-19.82892505766
a(5)	=	-39.12366319808
a(6)	=	-1.092943485307
a(7)	=	-60.60284446363
a(8)	=	10.43607464144
a(9)	=	104.2051224235
a(10)	=	1.555359815340
a(11)	=	29.43405714862
a(12)	=	-115.7160478956
a(13)	=	-5.442218832678
a(14)	=	66.88646322602
a(15)	=	-20.41011419418
a(16)	=	2.634078956636
a(17)	=	476.3125709212
a(18)	=	-1163.055871714
a(19)	=	222.8236602169
a(20)	=	2960.272074697
a(21)	=	-1238.369729565

I = 15.0

temperature range	:	80 - 1100 K
pressure range	:	1 - 1000 bar

mean error	=	.16 %
standard deviation	= +/-	1.15 %
absolute mean error	= +/-	.80 %
max. positive error	=	5.0 %
max. negative error	=	8.8 %
number of points	=	1541

Table C2. Transport equation of state (TEOS), thermal conductivity of nitrogen

critical temperature	=	126.200 K
critical pressure	=	34.0 bar
triplepoint temperature	=	63.1 K
molecular weight	=	28.013 kg/kmol
crit. thermal conductivity factor	=	4.173 mW/m·K

TEOS coefficients :

a(1)	=	-1.412333348830
a(2)	=	-24.39676450533
a(3)	=	92.12276400316
a(4)	=	-11.26375350991
a(5)	=	-120.0091559308
a(6)	=	9.088339876055
a(7)	=	-87.67039461229
a(8)	=	12.27193583572
a(9)	=	211.7614117578
a(10)	=	16.81947378288
a(11)	=	14.74404422899
a(12)	=	-349.4087239930
a(13)	=	-.5289415048724
a(14)	=	53.75114323814
a(15)	=	2.272339604306
a(16)	=	-.5665739767347
a(17)	=	-7.965717039555
a(18)	=	2.679432311347
a(19)	=	195.7707623345
a(20)	=	-1.688466746882
a(21)	=	.1755843250023E-01

I = .05

temperature range	:	70 - 1100 K
pressure range	:	1 - 1000 bar

mean error	=	-.01 %
standard deviation	= +/-	.83 %
absolute mean error	= +/-	.40 %
max. positive error	=	9.8 %
max. negative error	=	3.7 %
number of points	=	1609