THERMODYNAMIC PROPERTIES OF NITROGEN AT HIGH PRESSURES

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The thermodynamic properties of nitrogen and other industrially important gases have been adequately investigated in the range of parameters from the saturation line up to temperatures of 1300°K and pressures of 1000 bar [1] and, also, at temperatures up to 3000°K and pressures up to 100 bar [2]. These data were derived from the results of a considerable number of experimental investigations by various authors and are highly accurate. Results of systematic experimental research into the thermodynamic properties of gases at pressures of 10-12 kbar and comparatively low temperatures have been published by a number of authors. One of these is the monograph by Din [3] covering a range of pressures up to 10 kbar and temperatures up to 400°K, as well as the latest investigation by Tsiklis at pressures up to 12 kbar and temperatures up to 700°K.

Systematic, if only approximate, data on the thermodynamic properties of industrially important gases at pressures of 10-15 kbar and temperatures up to 3000°K are needed in technological applications. Hence the necessity to improve the methods of calculation of thermodynamic functions of real gases in this range of parameters.

The most general equation of state of gases of moderate density is of the virial form, which is an expansion of the compressibility factor z = pv/RT into power series of density:

$$z = 1 + B(T)\rho + C(T)\rho^2 + D(T)\rho^3 + \dots \tag{1}$$

where ρ is the gas density and B(T), C(T), D(T), etc., are, respectively, the second, third, fourth, and so forth virial coefficients.

Equation (1) cannot, however, be used for determining the thermodynamic properties of gases at very high densities. The domain of applicability of Eq. (1) with this or that number of terms of the virial expansion has not been so far exactly determined. The condition of smallness of the volume of a molecule relative to the volume of gas per molecule, used in the derivation of Eq. (1), is only a sufficient condition for the convergence of the series into which the binary function of molecule distribution in the gas is expanded. This condition defines the domain of applicability of Eq. (1) only approximately and does not take into account the number of terms used in the virial expansion.

An empirical or semiempirical function representing the dependence of intermolecular action on the distance (r) between molecules is used in the calculation of the dependence of virial coefficients on temperature. One of the most perfect forms of this function is the Lennard-Jones potential

$$U(r) = 4\varepsilon\left[\left(\frac{\sigma}{r}\right)^{12} - \left(\frac{\sigma}{r}\right)^{6}\right] \tag{2}$$

Parameters ε and σ appearing in (2) have the dimensions of energy and length, respectively, and define the chemical individuality of gas.

Actual calculation of virial coefficients of Eq. (1) with the use of potential (2) is very complicated and the amount of calculation considerably increases with the use of virial coefficients of higher order. Results published so far relate to the calculation of the second virial coefficient B(T) in the interval of relative

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temperature kT/ε = 0.3–400 (here k is Boltzmann's constant) and, also, of the third virial coefficient C(T) in the interval kT/ε = 0.7–400. These calculations were made by Hirschfelder [5].

The recently published paper by Barker et al. [6] gives the results of calculation of the fourth and fifth virial coefficients D(T) and E(T) in the interval kT/ε = 0.625–20 derived with the use of the molecular interaction potential (2). The third and fourth virial coefficients have now been calculated by Savel'ev for a wider range of kT/ε = 0.3–400, also, with the use of potential (2). These calculations are in good agreement with the data provided by Hirschfelder and Barker.

Another form of the equation of state of real gases, also recently published, is that of the Rawlinson's equation [7] derived by summing virial series (1). This is possible on certain assumptions which are, however, valid only on condition that

$$T \geqslant 12\varepsilon/k \tag{3}$$

which for nitrogen corresponds to T ≥ 1200°K.

Rawlinson's equation is of the form

$$z = \frac{1+\xi+\xi^2}{(1-\xi)^2} \tag{4}$$

in which ξ, if used with the molecular interaction potential (2), is defined by

$$\xi = \left(\frac{b_0}{4v}\right)\left(\frac{\varepsilon}{kT}\right)^{1/4}\left[1+\frac{1}{12}F\left(\frac{\varepsilon}{kT}\right)\right]^3 \tag{5}$$

Here b_0 is the second virial coefficient for models of hard spheres, v is the specific volume, and $F(\varepsilon/kT)$ is a certain function whose numerical values are given in [7] for a wide range of the argument.

It is also shown in [7] that the results of calculations by Eq. (4) are in good correlation with the data on the pressure of dense gases calculated by the Monte Carlo method on a computer, as well as with measurements of compressibility of gases at high normalized temperatures and with the results of certain measurements of the density of argon compressed by shock waves to a pressure of 200 kbar.

Thus in the range of pressures considered and temperatures T ≤ 700°K experimental data on the thermodynamic properties of nitrogen are available, while more or less reliable methods of calculation of these exist for temperatures T ≥ 1200°K. There are at present no methods whatsoever for determining the thermodynamic parameters of nitrogen in the interval between the isotherms of 700 and 1200°K, in which only empirical or semiempirical interpolation methods can be used.

The compressibility factor, the specific volume, the enthalpy and entropy of nitrogen calculated in the considered interval by Eq. (1) with five virial coefficients are in good correlation with data derived from Eq. (4) for temperatures from 1200 to 3000°K. However, for temperatures T < 700°K there is a discrepancy of 10–15% between these results and the experimental data cited in [4]. In the calculations with Eq. (1), ε/k = 91.5°K and σ = 3.681 Å were taken as parameters of the molecular interaction potential.

It should be noted that the numerical values of parameters ε and σ, experimentally determined by various researchers using different physical methods, vary considerably (see [5]), with the maximum and minimum values of ε/k for nitrogen being 95.9 and 79.8°K, and of σ 3.749 and 3.681 Å, respectively.

Numerous calculations of the thermodynamic properties of nitrogen using various values of ε and σ within the above range had shown that the effect of σ on the results of calculations is considerable for

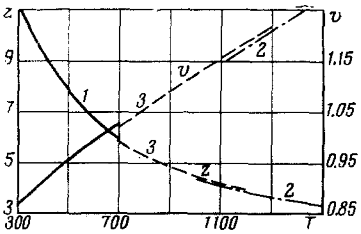

Fig. 1

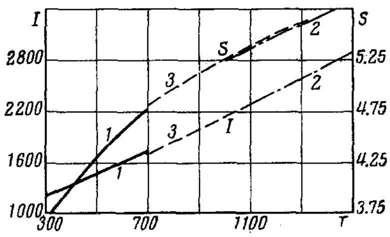

Fig. 2

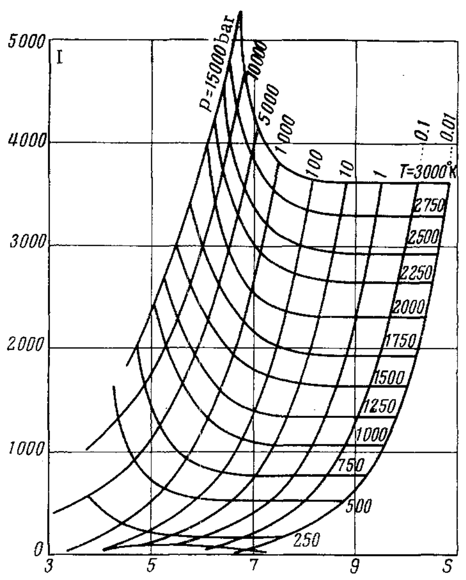

Fig. 3

temperatures around 700°K, while being virtually nil for temperatures T ≥ 1200°K. This is explained by the diminishing influence of the effective dimensions of molecules on the behavior of gas at reduced densities, when the properties of a real gas approach those of a perfect gas.

The reasoning and deductions presented above show the feasibility of devising a semiempirical method for calculating thermodynamic properties of gases in the considered range of pressures and at temperatures from 700 to 1200°K. If, in calculations via Eq. (1) with four or five virial coefficients, a certain fictitious value of σ, chosen so as to obtain matching of calculated results with experimental data at 700°K, is used instead of of the effective diameter of molecules, the derived results will be in good agreement with those calculated with (4) for the whole range of temperatures from 1200 to 3000°K.

As an example, the compressibility factor, the specific volume, and the enthalpy and entropy of nitrogen in the temperature interval 700-1200°K at pressure of 12 kbar, calculated by this method, are shown in Figs. 1 and 2 (curves denoted by the numerical 3). Numerals 1 and 2 denote, respectively, the experimental data from [4] and those calculated by the Rawlinson Eq. (4). Five virial coefficients were used in the calculations by Eq. (1). The generally accepted value of 91.5°K was taken for ε/k, and the value of σ was selected so as to obtain the smallest possible discrepancy between calculated and experimentally determined values of parameters at 700°K. It is seen from Figs. 1 and 2 that these discrepancies do not exceed 0.3% and are, consequently, within the limits of errors of related measurements (see [4]). The greatest divergence between calculated values of parameters and those derived by Eq. (4) for temperatures T ≥ 1200°K is in the specific volume of gas at T = 1200°K and is equal to 0.55%. The selected value of σ was 3.656 Å.

The calculated thermal and calorific properties of nitrogen at pressures up to 15 kbar and temperatures up to 3000°K are given in Tables 1 and 2, where, as well as in the figures, the following units are used: bar for pressure p; dm^3/kg for the specific volume v; kJ/kg for the enthalpy I; kJ/kg·deg for the entropy S; m/sec for the speed of sound a; kJ/kg·deg for the specific heat at constant pressure c_p. The calculations by Eq. (1) with five virial coefficients and the indicated above value of σ were made on a MINSK-22 computer. The expressions of calorific functions for nitrogen in terms of virial coefficients used in these calculations were obtained, unlike those in [5], by expressing these functions directly in terms of the free energy of gas

$$F = F_0 + RT\,[B\,(T)\,\rho + {}^1/_2 C\,(T)\,\rho^2 + {}^1/_3 D\,(T)\,\rho^3 + {}^1/_4 E\,(T)\,\rho^4] \tag{6}$$

where F_0 is the free energy of perfect gas.

The fifth virial coefficient E(T) was used in the calculations in a range of normalized temperatures kT/ε up to 30.

Values of this coefficient were derived by extrapolating the data given in [6] by means of formula

$$\frac{E\,(T)}{b_0^4} = \mathrm{A} + \frac{B}{kT/\varepsilon} \tag{7}$$

Constants A and B were determined from the data given in [6] for kT/ε equal 10 and 20.

The results of calculations of the thermodynamic properties of nitrogen in the range of temperatures of 1300-3000°K and of pressures of 100-1000 bar are given in Table 1, while Table 2 contains the same parameters for temperatures between 700 and 3000°K and pressures of 1-15 kbar. At the limits of these ranges these data are in good agreement with those of [1, 2, 4]. The tabulated data are, also, in good agreement with the values of specific volume, enthalpy, and entropy calculated by Eq. (4) throughout the range of pressures and for temperatures ranging from 1200 to 3000°K.

TABLE 1

T, °K	v	I	S	a	c_p	c_p/c_v
			$p = 100$ bar			
1300	39.66	1445	7.094	736.0	1.220	1.325
1400	42.72	1568	7.185	760.9	1.233	1.319
1500	45.58	1692	7.271	758.1	1.243	1.314
1600	48.62	1817	7.352	808.4	1.254	1.311
1700	51.66	1943	7.428	831.1	1.263	1.308
1800	54.70	2070	7.501	853.1	1.271	1.305
1900	57.51	2198	7.570	874.8	1.278	1.303
2000	60.54	2326	7.636	895.9	1.284	1.301
2100	63.56	2455	7.699	916.6	1.289	1.299
2200	66.33	2585	7.759	936.8	1.294	1.297
2300	69.34	2715	7.817	956.6	1.299	1.296
2400	72.36	2845	7.872	976.0	1.303	1.295
2500	75.37	2976	7.925	995.0	1.307	1.293
2600	78.39	3106	7.977	1014	1.310	1.292
2700	81.40	3238	8.026	1032	1.313	1.291
2800	84.41	3369	8.074	1050	1.316	1.291
2900	87.43	3501	8.120	1068	1.318	1.290
3000	90.09	3634	8.165	1085	1.322	1.289
			$p = 200$ bar			
1300	20.41	1455	6.887	759.9	1.220	1.327
1400	21.98	1578	6.979	781.9	1.232	1.321
1500	23.45	1703	7.065	805.3	1.243	1.316
1600	24.91	1828	7.146	828.8	1.255	1.312
1700	26.36	1955	7.222	850.1	1.262	1.309
1800	27.91	2081	7.295	871.3	1.270	1.306
1900	29.34	2208	7.364	892.5	1.277	1.304
2000	30.88	2337	7.430	913.1	1.283	1.300
2100	32.30	2467	7.493	933.4	1.288	1.299
2200	33.83	2596	7.553	953.2	1.295	1.297
2300	35.23	2726	7.611	927.7	1.298	1.296
2400	36.76	2857	7.666	991.6	1.302	1.295
2500	38.29	2987	7.720	1010	1.306	1.293
2600	39.82	3119	7.771	1028	1.309	1.292
2700	41.19	3250	7.821	1046	1.312	1.291
2800	42.72	3381	7.869	1064	1.315	1.290
2900	44.24	3513	7.915	1082	1.318	1.290
3000	45.58	3646	7.960	1099	1.320	1.289
			$p = 300$ bar			
1300	14.01	1465	6.766	779.4	1.219	1.329
1400	15.02	1589	6.858	802.7	1.231	1.323
1500	16.03	1714	6.944	825.4	1.242	1.317
1600	17.02	1839	7.025	847.3	1.252	1.313
1700	17.94	1966	7.102	868.9	1.261	1.310
1800	18.99	2092	7.174	889.3	1.269	1.307
1900	19.96	2220	7.243	909.9	1.276	1.304
2000	20.93	2349	7.309	930.2	1.282	1.302
2100	21.98	2478	7.373	949.9	1.287	1.300
2200	22.92	2608	7.433	969.4	1.292	1.298
2300	23.87	2738	7.491	988.5	1.296	1.296
2400	24.91	2869	7.546	1007	1.300	1.295
2500	25.95	2999	7.600	1025	1.304	1.293
2600	26.87	3130	7.651	1043	1.308	1.292
2700	27.79	3262	7.700	1061	1.311	1.291
2800	28.82	3393	7.748	1078	1.314	1.290
2900	29.85	3525	7.795	1095	1.317	1.289
3000	30.88	3658	7.840	1112	1.319	1.289

TABLE 1 (continued)

T, °K	v	I	S	a	c_p	c_p/c_v
			$p = 400$ bar			
1300	10.78	1475	6.680	801.0	1.218	1.331
1400	11.56	1600	6.772	823.3	1.230	1.324
1500	12.28	1725	6.858	845.4	1.241	1.318
1600	13.04	1851	6.939	866.6	1.251	1.314
1700	13.80	1977	7.016	887.1	1.260	1.310
1800	14.49	2103	7.089	907.4	1.268	1.306
1900	15.23	2231	7.158	927.4	1.275	1.305
2000	15.96	2360	7.224	947.2	1.280	1.302
2100	16.76	2490	7.287	966.4	1.286	1.300
2200	17.48	2620	7.347	985.5	1.291	1.298
2300	18.20	2750	7.405	1004	1.295	1.296
2400	18.99	2880	7.461	1022	1.299	1.295
2500	19.70	3011	7.514	1040	1.303	1.293
2600	20.40	3142	7.566	1058	1.307	1.292
2700	21.19	3273	7.615	1075	1.310	1.291
2800	21.88	3405	7.663	1093	1.313	1.290
2900	22.67	3537	7.710	1109	1.316	1.289
3000	23.35	3670	7.754	1126	1.318	1.288
			$p = 500$ bar			
1300	8.858	1486	6.613	822.2	1.217	1.332
1400	9.454	1610	6.705	844.0	1.229	1.325
1500	10.04	1736	6.792	865.2	1.240	1.319
1600	10.66	1862	6.873	885.5	1.249	1.315
1700	11.23	1988	6.950	905.7	1.258	1.311
1800	11.84	2114	7.022	924.9	1.267	1.308
1900	12.44	2242	7.091	944.3	1.273	1.305
2000	13.04	2372	7.158	963.7	1.279	1.302
2100	13.64	2501	7.221	982.6	1.285	1.300
2200	14.22	2631	7.281	1001	1.289	1.298
2300	14.81	2762	7.339	1020	1.294	1.296
2400	15.39	2892	7.395	1038	1.298	1.294
2500	15.96	3023	7.448	1055	1.301	1.293
2600	16.60	3154	7.500	1072	1.305	1.292
2700	17.17	3285	7.549	1089	1.309	1.291
2800	17.73	3417	7.597	1106	1.312	1.290
2900	18.36	3549	7.643	1122	1.315	1.289
3000	18.91	3682	7.688	1139	1.317	1.288
			$p = 600$ bar			
1300	7.551	1496	6.558	843.6	1.216	1.334
1400	8.058	1621	6.651	864.3	1.227	1.326
1500	8.555	1747	6.737	884.8	1.238	1.320
1600	9.065	1873	6.819	904.2	1.248	1.315
1700	9.567	1999	6.895	923.7	1.257	1.311
1800	10.04	2125	6.968	942.6	1.265	1.309
1900	10.55	2254	7.037	961.4	1.272	1.306
2000	11.06	2383	7.103	980.2	1.278	1.304
2100	11.56	2513	7.167	998.7	1.283	1.301
2200	12.01	2643	7.227	1017	1.288	1.298
2300	12.55	2773	7.285	1035	1.293	1.296
2400	13.04	2904	7.341	1052	1.297	1.294
2500	13.53	3045	7.394	1070	1.302	1.293
2600	14.01	3166	7.446	1087	1.304	1.292
2700	14.49	3297	7.495	1113	1.308	1.291
2800	15.02	3429	7.543	1120	1.311	1.290
2900	15.49	3561	7.589	1136	1.313	1.289
3000	15.96	3694	7.634	1152	1.316	1.288

TABLE 1 (continued)

T, °K	v	I	S	a	c_p	c_p/c_v
			$p = 700$ bar			
1300	6.655	1507	6.512	863.8	1.214	1.335
1400	7.063	1632	6.604	884.4	1.226	1.327
1500	7.502	1758	6.691	903.9	1.237	1.320
1600	7.929	1834	6.772	923.1	1.246	1.316
1700	8.349	2010	6.849	941.8	1.255	1.312
1800	8.761	2137	6.922	960.0	1.264	1.309
1900	9.206	2253	6.991	978.2	1.272	1.306
2000	9.605	2395	7.058	997.0	1.277	1.304
2100	10.04	2524	7.121	1015	1.282	1.301
2200	10.47	2655	7.182	1033	1.287	1.298
2300	10.90	2785	7.239	1050	1.291	1.296
2400	11.32	2916	7.295	1067	1.295	1.294
2500	11.74	3047	7.349	1084	1.299	1.293
2600	12.16	3178	7.400	1101	1.303	1.292
2700	12.58	3309	7.450	1117	1.306	1.291
2800	12.99	3441	7.497	1133	1.309	1.290
2900	13.45	3573	7.544	1149	1.312	1.289
3000	13.85	3705	7.589	1165	1.315	1.288
			$p = 800$ bar			
1300	5.964	1517	6.472	884.3	1.212	1.336
1400	6.331	1643	6.564	903.9	1.224	1.327
1500	6.719	1769	6.651	922.5	1.235	1.321
1600	7.084	1895	6.733	941.3	1.245	1.316
1700	7.440	2022	6.809	959.7	1.254	1.312
1800	7.805	2148	6.882	977.3	1.263	1.309
1900	8.202	2276	6.952	994.7	1.270	1.306
2000	8.555	2406	7.018	1013	1.275	1.303
2100	8.943	2536	7.081	1030	1.280	1.300
2200	9.327	2666	7.142	1048	1.285	1.293
2300	9.665	2797	7.200	1065	1.290	1.296
2400	10.04	2928	7.256	1082	1.294	1.294
2500	10.41	3059	7.309	1099	1.298	1.293
2600	10.78	3190	7.360	1111	1.302	1.292
2700	11.11	3320	7.410	1131	1.305	1.291
2800	11.51	3452	7.458	1147	1.308	1.290
2900	11.87	3585	7.504	1163	1.311	1.289
3000	12.28	3717	7.549	1178	1.314	1.288
			$p = 900$ bar			
1300	5.406	1528	6.436	905.4	1.210	1.336
1400	5.765	1653	6.529	923.0	1.222	1.328
1500	6.088	1780	6.616	941.6	1.233	1.321
1600	6.432	1906	6.698	959.1	1.243	1.316
1700	6.737	2033	6.774	977.3	1.252	1.312
1800	7.067	2159	6.847	994.2	1.261	1.309
1900	7.391	2287	6.916	1012	1.268	1.306
2000	7.744	2417	6.983	1029	1.274	1.303
2100	8.058	2547	7.046	1046	1.279	1.300
2200	8.403	2678	7.107	1063	1.284	1.298
2300	8.746	2808	7.165	1080	1.289	1.296
2400	9.044	2940	7.221	1106	1.293	1.294
2500	9.379	3070	7.274	1113	1.297	1.293
2600	9.711	3201	7.326	1129	1.300	1.292
2700	10.04	3332	7.375	1144	1.304	1.290
2800	10.37	3464	7.425	1160	1.307	1.289
2900	10.69	3596	7.470	1176	1.310	1.288
3000	11.01	3729	7.515	1191	1.313	1.287

TABLE 1 (continued)

T, °K	v	I	S	a	c_p	c_p/c_v
			$p = 1000$ bar			
1300	4.988	1538	6.404	924.9	1.209	1.337
1400	5.292	1665	6.497	942.6	1.220	1.328
1500	5.586	1791	6.584	960.3	1.231	1.321
1600	5.901	1917	6.666	977.0	1.241	1.316
1700	6.180	2044	6.743	994.5	1.251	1.312
1800	6.481	2170	6.816	1011	1.260	1.310
1900	6.777	2298	6.885	1028	1.267	1.306
2000	7.067	2428	6.952	1045	1.272	1.303
2100	7.369	2559	7.015	1062	1.278	1.300
2200	7.667	2689	7.076	1078	1.283	1.298
2300	7.979	2820	7.134	1094	1.287	1.296
2400	8.251	2951	7.190	1111	1.291	1.294
2500	8.555	3082	7.243	1127	1.295	1.292
2600	8.860	3213	7.295	1142	1.299	1.291
2700	9.158	3344	7.344	1158	1.303	1.290
2800	9.454	3475	7.392	1173	1.306	1.289
2900	9.749	3608	7.483	1188	1.309	1.288
3000	10.04	3741	7.483	1204	1.311	1.287

TABLE 2

T, °K	v	I	S	a	c_p	c_p/c_v
			$p = 1000$ bar			
700	3.119	804.6	5.652	831.8	1.111	1.452
800	3.434	923.3	5.811	843.6	1.132	1.421
1000	4.063	1166	6.079	873.3	1.167	1.377
1200	4.675	1413	6.304	907.7	1.196	1.348
1400	5.292	1665	6.497	942.6	1.220	1.328
1600	5.900	1917	6.666	976.9	1.241	1.316
1800	6.481	2169	6.815	1011	1.259	1.309
2000	7.067	2428	6.952	1045	1.272	1.303
2200	7.667	2689	7.075	1078	1.283	1.298
2400	8.250	2951	7.189	1111	1.291	1.293
2600	8.858	3212	7.295	1142	1.299	1.291
2800	9.454	3475	7.392	1173	1.306	1.289
3000	10.04	3741	7.483	1204	1.311	1.287
			$p = 1500$ bar			
700	2.433	851.0	5.523	966.3	1.094	1.456
800	2.644	970.7	5.683	968.6	1.122	1.423
1000	3.060	1214	5.954	985.5	1.158	1.381
1200	3.483	1465	6.181	1008	1.185	1.350
1400	3.896	1719	6.376	1035	1.210	1.329
1600	4.288	1973	6.545	1064	1.232	1.316
1800	4.675	2225	6.695	1093	1.252	1.310
2000	5.078	2484	6.831	1122	1.265	1.303
2200	5.476	2747	6.956	1152	1.276	1.297
2400	5.872	3009	7.070	1181	1.285	1.293
2600	6.271	3271	7.175	1210	1.293	1.290
2800	6.658	3533	7.272	1238	1.300	1.288
3000	7.034	3799	7.364	1267	1.306	1.286

TABLE 2 (continued)

T, °K	v	I	S	a	c_p	c_p/c_v
			$p = 2000$ bar			
700	2.081	898.7	5.431	1086	1.078	1.458
800	2.243	1019	5.592	1080	1.116	1.422
1000	2.558	1264	5.865	1088	1.150	1.383
1200	2.876	1517	6.093	1102	1.174	1.352
1400	3.184	1773	6.289	1122	1.199	1.329
1600	3.483	2028	6.459	1146	1.223	1.316
1800	3.778	2279	6.609	1169	1.244	1.309
2000	4.074	2540	6.746	1195	1.258	1.302
2200	4.375	2803	6.871	1221	1.269	1.296
2400	4.675	3065	6.984	1248	1.279	1.292
2600	4.963	3328	7.090	1274	1.287	1.289
2800	5.265	3590	7.188	1300	1.295	1.287
3000	5.559	3856	7.279	1326	1.300	1.285
			$p = 2500$ bar			
700	1.866	945.8	5.359	1193	1.064	1.458
800	1.993	1067	5.520	1183	1.111	1.421
1000	2.251	1314	5.795	1182	1.144	1.384
1200	2.506	1517	6.025	1190	1.163	1.354
1400	2.754	1826	6.222	1204	1.188	1.329
1600	2.992	2082	6.392	1223	1.213	1.316
1800	3.227	2334	6.542	1243	1.236	1.309
2000	3.463	2595	6.679	1266	1.251	1.301
2200	3.704	2859	6.807	1289	1.262	1.295
2400	3.942	3122	6.919	1312	1.272	1.291
2600	4.181	3384	7.024	1336	1.282	1.288
2800	4.408	3647	7.122	1360	1.290	1.286
3000	4.651	3912	7.214	1384	1.296	1.284
			$p = 3000$ bar			
700	1.713	993.8	5.299	1292	1.052	1.460
800	1.821	1116	5.461	1276	1.110	1.418
1000	2.038	1363	5.737	1271	1.140	1.384
1200	2.251	1620	5.969	1274	1.153	1.356
1400	2.462	1879	6.166	1281	1.177	1.330
1600	2.666	2115	6.338	1295	1.204	1.315
1800	2.858	2387	6.488	1313	1.228	1.308
2000	3.060	2648	6.625	1331	2.244	1.300
2200	3.258	2913	6.751	1352	1.256	1.294
2400	3.453	3177	6.862	1374	1.266	1.290
2600	3.658	3438	6.970	1395	1.276	1.287
2800	3.843	3702	7.068	1418	1.284	1.285
3000	4.041	3968	7.160	1440	1.291	1.283
			$p = 3500$ bar			
700	1.601	1040	5.248	1383	1.043	1.462
800	1.693	1162	5.411	1360	1.112	1.416
1000	1.883	1412	5.638	1353	1.138	1.385
1200	2.067	1670	5.921	1352	1.143	1.358
1400	2.251	1930	6.120	1353	1.166	1.330
1600	2.420	2189	6.291	1366	1.194	1.315
1800	2.588	2441	6.442	1380	1.221	1.307
2000	2.765	2702	6.579	1395	1.237	1.300
2200	2.930	2968	6.705	1415	1.250	1.293
2400	3.101	3232	6.820	1434	1.261	1.289
2600	3.272	3494	6.925	1453	1.271	1.286
2800	3.434	3757	7.023	1474	1.280	1.284
3000	3.608	4023	7.115	1494	1.286	1.282

TABLE 2 (continued)

T, °K	v	I	S	a	c_p	c_p/c_v
			$p = 4000$ bar			
700	1.515	1086	5.203	1466	1.034	1.464
800	1.599	1209	5.366	1440	1.115	1.413
1000	1.767	1458	5.645	1423	1.137	1.386
1200	1.927	1719	5.879	1426	1.134	1.361
1400	2.085	1982	6.079	1424	1.156	1.330
1600	2.243	2239	6.251	1430	1.185	1.315
1800	2.387	2492	6.401	1443	1.214	1.307
2000	2.541	2754	6.540	1456	1.231	1.293
2200	2.687	3021	6.665	1473	1.244	1.292
2400	2.840	3284	6.780	1489	1.255	1.288
2600	2.984	3548	6.886	1509	1.266	1.285
2800	3.128	3810	6.983	1528	1.275	1.284
3000	3.275	4078	7.075	1547	1.282	1.281
			$p = 5000$ bar			
700	1.386	1176	5.125	1620	1.020	1.468
800	1.456	1300	5.290	1583	1.055	1.401
1000	1.591	1553	5.571	1572	1.080	1.387
1200	1.724	1816	5.808	1564	1.118	1.367
1400	1.854	2082	6.010	1553	1.136	1.333
1600	1.977	2342	6.183	1556	1.167	1.316
1800	2.096	2595	6.334	1563	1.200	1.306
2000	2.218	2858	6.473	1572	1.219	1.297
2200	2.338	3126	6.599	1585	1.233	1.291
2400	2.464	3389	6.714	1597	1.246	1.286
2600	2.582	3652	6.819	1613	1.257	1.284
2800	2.693	3916	6.917	1631	1.266	1.282
3000	2.814	4183	7.010	1646	1.273	1.280
			$p = 7000$ bar			
700	1.223	1350	5.003	1885	0.999	1.477
800	1.277	1474	5.169	1865	1.127	1.395
1000	1.378	1732	5.454	1817	1.054	1.389
1200	1.478	2001	5.697	1809	1.089	1.382
1400	1.575	2272	5.904	1783	1.097	1.341
1600	1.666	2536	6.079	1775	1.134	1.319
1800	1.752	2791	6.231	1777	1.177	1.306
2000	1.839	3058	6.418	1780	1.199	1.296
2200	1.929	3325	6.498	1785	1.215	1.289
2400	2.019	3590	6.614	1792	1.223	1.284
2600	2.106	3854	6.720	1804	1.241	1.282
2800	2.186	4119	6.818	1819	1.252	1.280
3000	2.273	4387	6.910	1830	1.259	1.278
			$p = 9000$ bar			
700	1.120	1518	4.906	2112	0.936	1.485
800	1.164	1643	5.073	2079	1.000	1.381
1000	1.248	1903	5.362	2056	1.027	1.390
1200	1.328	2178	5.610	2027	1.064	1.400
1400	1.407	2455	5.823	1936	1.061	1.351
1600	1.480	2722	6.000	1971	1.104	1.325
1800	1.550	2977	6.153	1965	1.157	1.307
2000	1.619	3247	6.294	1963	1.182	1.296
2200	1.688	3519	6.421	1965	1.199	1.288
2400	1.758	3786	6.538	1970	1.214	1.284
2600	1.829	4048	6.644	1976	1.228	1.281
2800	1.895	4313	6.742	1938	1.240	1.280
3000	1.963	4582	6.835	1995	1.247	1.277

TABLE 2 (continued)

T, °K	v	I	S	a	c_p	c_p/c_v
			$p = 11\,000$ bar			
700	1.049	1676	4.825	2307	0.977	1.492
800	1.087	1802	4.993	2260	0.997	1.467
1000	1.158	2066	5.235	2229	1.019	1.388
1200	1.228	2344	5.539	2221	1.041	1.380
1400	1.291	2633	5.756	2174	1.066	1.363
1600	1.353	2902	5.935	2149	1.075	1.332
1800	1.413	3160	6.039	2140	1.139	1.309
2000	1.473	3427	6.231	2127	1.167	1.296
2200	1.531	3701	6.359	2126	1.186	1.288
2400	1.590	3969	6.476	2126	1.202	1.283
2600	1.644	4239	6.583	2136	1.216	1.281
2800	1.700	4502	6.681	2144	1.229	1.280
3000	1.756	4773	6.775	2150	1.237	1.276
			$p = 13\,000$ bar			
700	0.995	1831	4.753	2587	0.971	1.498
800	1.029	1956	4.923	2553	0.999	1.354
1000	1.092	2221	5.217	2470	1.007	1.386
1200	1.152	2507	5.476	2404	1.020	1.441
1400	1.208	2808	5.699	2346	1.031	1.378
1600	1.261	3076	5.880	2314	1.046	1.341
1800	1.315	3332	6.035	2292	1.123	1.312
2000	1.365	3605	6.177	2281	1.154	1.300
2200	1.417	3877	6.307	2273	1.174	1.289
2410	1.465	4151	6.424	2275	1.491	1.284
2600	1.516	4415	6.531	2278	1.207	1.231
2800	1.562	4683	6.630	2288	1.220	1.280
3000	1.603	4958	6.723	2292	1.228	1.277
			$p = 15\,000$ bar			
700	0.952	1982	4.691	2749	0.967	1.503
800	0.932	2108	4.860	2691	0.980	1.440
1000	1.039	2376	5.157	2620	0.999	1.420
1200	1.093	2666	5.420	2578	1.000	1.380
1400	1.144	2965	5.649	2505	1.059	1.364
1600	1.192	3240	5.831	2464	1.079	1.350
1800	1.238	3501	5.937	2438	1.108	1.316
2000	1.282	3778	6.131	2423	1.142	1.300
2200	1.326	4054	6.261	2414	1.163	1.290
2400	1.370	4328	6.379	2413	1.181	1.285
2600	1.416	4590	6.486	2413	1.193	1.282
2800	1.458	4857	6.585	2421	1.212	1.281
3000	1.500	5130	6.679	2422	1.221	1.277

The I–S diagram for nitrogen is shown in Fig. 3 in a wide range of parameters from the saturation line to a pressure of 15 kbar and temperature up to 3000°K. The diagram was drawn up from data in [1–4] and in Tables 1 and 2. One of the most distinctive features of the behavior of gas at high pressures is clearly seen in the diagram. This is the sharp rise of isotherms with increasing pressure, which for nitrogen begins at 1000 bar. It is explained by the fact that the enthalpy of a real gas, unlike that of a perfect one, depends not only on temperature but, also on pressure.

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