Viscosity of Gaseous Nitrous Oxide from 298.15 K to 398.15 K at Pressures up to 25 MPa

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The viscosity of gaseous nitrous oxide was measured using an oscillating disk viscometer of the Maxwell type from 298.15 K to 398.15 K at pressures up to 25 MPa. The results were fitted to an empirical equation as a function of temperature and density. The Chung and Lee−Thodos correlations were tested to fit the experimental viscosity values.

Introduction

The viscosity of gaseous nitrous oxide at normal pressure has been measured by many investigators (Fisher, 1909; Vogel, 1914; Trautz and Kurz, 1931; Johnston and McClosky, 1940; Raw and Ellis, 1958; Ellis and Raw, 1959; Uchiyama, 1965; Chakraborti and Gray, 1965; Kestin and Wakeham, 1979; Harris et al., 1979; Clifford et al., 1981; Kestin and Ro, 1982). Measurements at higher pressures have been made by Schlumpf et al. (1975) and Yokoyama et al. (1994). The experimental data of Schlumpf et al. were given graphically. The experimental range of Yokoyama et al. was limited within the critical point. In this study, the viscosity of gaseous nitrous oxide was measured from 298.15 K to 398.15 K at pressures up to 25 MPa. The results were fitted to an empirical equation as a function of temperature and density. The experimental results were compared to the Chung (1988) and Lee−Thodos equations (1988), and the deviations of experimental viscosity from each equation were compared.

Experimental Section

The viscosity was measured using an oscillating disk viscometer of the Maxwell type. The experimental apparatus and procedure were essentially the same as those described in the previous papers (Takahashi et al., 1988, 1989, 1995). The apparatus constant at the experimental temperature and pressure conditions was determined using the viscosity data of nitrogen taken from Stephan et al. (1987) and the gas density data of nitrogen from Jacobsen et al. (1973). Temperature and pressure values have an uncertainty of ±0.01 K and ±0.5 kPa, respectively. Density values obtained from the compressibility data of Couch et al. (1961) have an uncertainty of ±0.03 kg·m^{-3}. This rather large uncertainty of density could not reduce the accuracy of the viscosity measurements. It is well-known that the viscosity values obtained from the Newell theory are extremely insensitive to the density value used. The viscosity is proportional to $\rho\delta^2$, where ρ is density and δ is a boundary layer thickness. The boundary layer thickness is a function of density. The effect of density on boundary layer thickness compensates for the variation of density value. The error in the measurements of viscosity was estimated to be ±0.3%. The sample was supplied by Showa Denko Co., Ltd., and was used as received. The purity of the sample was approximately 99.5%.

Results and Discussion

The previous experimental data of the viscosity of nitrous oxide are presented in Table 1. The temperature and

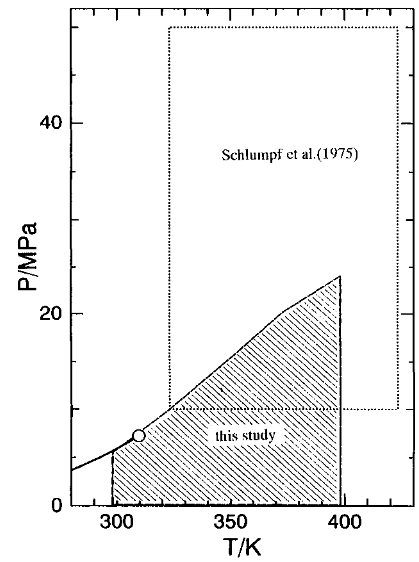

Figure 1. Temperature and pressure regions of viscosity measurements in this study and by Schlumpf et al. (1975), saturated vapor pressure, and critical point of nitrous oxide: (- - -) this study; (···) Schlumpf et al. (1975); (—) saturated vapor pressure; (○) critical point.

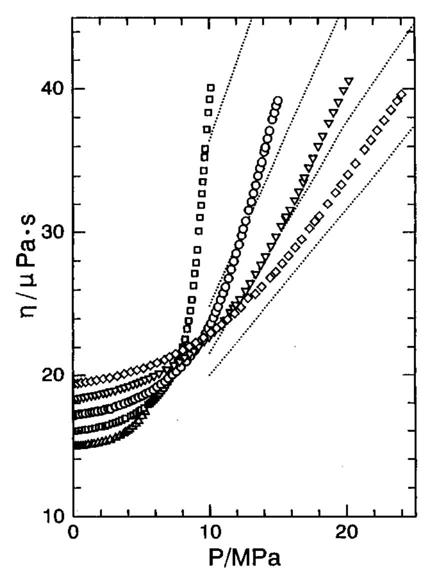

Figure 2. Plots of viscosity η as a function of pressure P for nitrous oxide. This study: (△) 298.15 K; (□) 323.15 K; (○) 348.15 K; (▽) 373.15 K; (◇) 398.15 K. (···) Schlumpf et al. (1975).

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Table 1. Experimental Studies of Viscosity of Nitrous Oxide

author	year	method	temp range/K	pressure range/bar	no. of data	precision
Fischer	1909	capillary	299−687	1.013	8	
Vogel	1914	oscillating disk	273	0.320	1	
Trautz and Kurz	1931	capillary	300−550	1.013	6	
Johnston and McClosky	1940	oscillating disk	185−300	1.013	10	2.0%−3.0%
Raw and Ellis	1958	capillary	429−1296	1.013	15	1%
Chakraborti and Gray	1965	capillary	298−353	1.013	3	0.3%
Schlumpf	1975	capillary	323−423	100−500	25	3.5%
Harris et al.	1979	capillary	197−277	1.013	5	1.0%−1.3%
Kestin and Wakeham	1979	oscillating disk	301−473	1.013	5	0.2%−0.3%
Clifford et al.	1981	capillary	372−773	1.013	5	1.5%
Kestin and Ro	1982	oscillating disk	298−473	1.013	30	0.2%−0.3%
Yokoyama et al.	1994	oscillating disk	310−318	1−96	373	0.6%
Takahashi et al.	1996	oscillating disk	298−398	1−240	275	0.3%

Table 2. Density ρ and Viscosity η of Nitrous Oxide

P/MPa	ρ/kg·m^{-3}	η/μPa·s	P/MPa	ρ/kg·m^{-3}	η/μPa·s	P/MPa	ρ/kg·m^{-3}	η/μPa·s	P/MPa	ρ/kg·m^{-3}	η/μPa·s	P/MPa	ρ/kg·m^{-3}	η/μPa·s	P/MPa	ρ/kg·m^{-3}	η/μPa·s
								T = 298.15 K									
0.1013	1.809	14.90	1.521	29.55	15.07	3.988	96.24	16.01	0.6880	12.70	14.94	3.096	68.06	15.52	5.061	141.2	17.07
0.1591	2.850	14.92	1.788	35.40	15.14	4.097	100.2	16.13	0.8856	16.55	14.97	3.399	76.98	15.68	5.273	153.7	17.39
0.2092	3.758	14.90	2.101	42.55	15.21	4.340	109.2	16.30	1.083	20.46	15.01	3.690	86.16	15.83	5.524	172.1	17.90
0.3496	6.329	14.91	2.376	49.13	15.28	4.564	117.1	16.52	1.332	25.56	15.04	3.824	90.58	15.95			
0.5168	9.447	14.92	2.684	56.90	15.36	4.786	127.2	16.72									
								T = 323.15 K									
0.1018	1.674	15.98	4.969	107.3	17.52	8.174	265.1	22.59	2.541	46.89	16.44	6.758	173.6	19.28	9.362	436.7	31.92
0.1025	1.687	16.01	5.176	113.7	17.66	8.341	281.4	23.29	2.831	53.08	16.53	6.918	181.3	19.48	9.428	449.5	32.76
0.2047	3.382	16.01	5.473	123.4	17.89	8.460	294.2	23.85	3.086	58.68	16.62	7.053	188.3	19.73	9.496	462.2	33.63
0.5847	9.823	16.06	5.600	127.6	17.99	8.580	308.2	24.56	3.316	63.91	16.69	7.216	197.0	20.00	9.566	474.0	34.40
0.8354	14.20	16.08	5.723	131.9	18.09	8.697	324.8	25.31	3.558	69.60	16.80	7.330	203.4	20.23	9.645	487.5	35.30
1.045	17.93	16.13	5.870	138.5	18.21	8.829	342.2	26.28	3.803	75.59	16.91	7.468	211.8	20.52	9.688	495.0	35.85
1.339	23.29	16.15	6.019	142.7	18.37	8.913	355.0	27.02	4.208	85.98	17.09	7.645	223.4	20.93	9.808	511.9	37.17
1.590	27.98	16.22	6.167	148.3	18.53	9.006	370.3	27.87	4.390	90.79	17.17	7.819	235.7	21.41	9.919	525.9	38.33
1.853	33.01	16.28	6.297	153.5	18.67	9.091	385.2	28.76	4.618	97.13	17.29	7.872	239.9	21.55	10.02	537.4	39.24
2.068	37.27	16.33	6.451	159.9	18.86	9.209	407.3	30.09	4.818	102.9	17.43	8.023	251.9	22.03			
2.337	42.69	16.36	6.614	167.0	19.06	9.290	422.7	31.06									
								T = 348.15 K									
0.1014	1.546	17.12	5.572	105.9	18.80	11.60	338.1	27.42	2.301	37.88	17.54	9.177	218.5	22.18	13.72	460.1	34.55
0.1015	1.547	17.15	5.850	112.8	18.95	11.79	349.3	27.97	2.558	42.53	17.61	9.456	230.1	22.54	13.85	467.0	34.95
0.2082	3.186	17.20	6.129	120.0	19.14	11.96	359.4	28.52	2.749	46.06	17.60	9.694	240.4	22.95	14.01	474.6	35.65
0.3475	5.342	17.20	6.430	128.0	19.34	12.15	370.8	29.14	3.082	52.33	17.75	9.895	249.5	23.32	14.11	480.8	35.95
0.4945	7.636	17.19	6.716	135.8	19.54	12.34	382.1	29.76	3.406	58.62	17.86	10.09	258.4	23.66	14.27	489.9	36.54
0.6991	10.87	17.24	6.936	142.1	19.77	12.46	389.1	30.21	3.742	65.34	17.98	10.27	267.4	24.07	14.43	496.3	37.08
0.9053	14.17	17.27	7.281	152.3	20.01	12.64	399.9	30.79	4.067	72.01	18.10	10.44	275.9	24.45	14.63	505.4	37.86
1.181	18.65	17.31	7.554	160.7	20.25	12.85	412.0	31.57	4.308	77.11	18.20	10.61	284.5	24.82	14.78	512.1	38.32
1.398	22.26	17.37	7.890	171.4	20.57	13.07	424.6	32.18	4.500	81.24	18.29	10.82	295.0	25.30	14.91	517.7	38.82
1.594	25.57	17.40	8.285	184.9	21.00	13.23	433.8	32.79	4.771	87.20	18.41	10.99	304.4	25.75	15.05	523.6	39.17
1.796	29.02	17.43	8.583	195.6	21.37	13.38	442.2	33.36	5.054	93.58	18.52	11.17	314.1	26.19			
2.093	34.20	17.46	8.873	204.4	21.74	13.56	451.8	34.03	5.303	99.43	18.67	11.39	326.3	26.78			
								T = 373.15 K									
0.1003	1.426	18.34	5.903	99.77	19.93	13.77	318.1	27.72	2.460	37.24	18.75	9.956	196.5	22.71	16.96	429.5	33.91
0.1015	1.445	18.30	6.290	107.7	20.13	14.10	330.2	28.30	2.719	41.47	18.84	10.34	210.0	23.10	17.28	439.9	34.60
0.1017	1.445	18.35	6.835	119.4	20.42	14.51	344.7	29.04	3.073	47.37	18.91	10.67	217.0	23.43	17.60	450.2	35.24
0.2564	3.653	18.36	6.857	119.9	20.42	14.87	357.4	29.69	3.449	53.78	19.03	11.09	229.7	23.91	17.97	461.6	36.05
0.5026	7.214	18.39	7.381	131.6	20.73	15.26	371.0	30.45	3.748	58.99	19.10	11.53	243.1	24.44	18.31	471.3	36.72
0.7620	11.01	18.42	7.789	141.0	20.98	15.59	382.6	30.98	4.065	64.62	19.20	11.79	251.4	24.74	18.75	484.0	37.62
1.024	14.89	18.46	8.161	149.9	21.29	15.61	383.3	31.10	4.371	70.15	19.32	11.93	255.9	24.97	19.10	493.6	38.35
1.340	19.65	18.52	8.539	159.2	21.54	15.91	393.6	31.61	4.678	75.85	19.43	12.23	265.6	25.34	19.45	503.2	39.06
1.613	23.83	18.58	8.832	166.6	21.75	16.24	405.4	32.30	4.978	81.53	19.53	12.64	279.5	25.94	19.84	513.3	39.89
1.882	28.03	18.62	9.202	176.2	22.04	16.54	415.5	32.92	5.253	86.83	19.66	12.99	291.2	26.46	20.21	522.7	40.58
2.203	33.10	18.70	9.606	186.9	22.43	16.88	427.0	33.59	5.563	92.93	19.78	13.38	304.6	27.09			
								T = 398.15 K									
0.1023	1.361	19.41	8.026	128.4	21.80	16.74	330.6	29.48	3.714	53.43	20.10	12.32	220.4	24.78	21.36	441.5	35.80
0.3425	4.581	19.41	8.506	137.9	22.05	17.31	345.7	30.26	4.214	61.34	20.24	12.82	232.5	25.23	21.84	452.1	36.45
0.5963	8.015	19.46	8.975	147.2	22.33	17.71	355.1	30.76	4.642	68.29	20.37	13.36	245.6	25.71	22.28	461.6	37.10
0.9220	12.47	19.50	9.556	159.1	22.67	18.03	363.2	31.15	5.135	76.43	20.50	13.83	257.0	26.19	22.78	472.2	37.79
1.316	17.94	19.56	10.07	170.1	23.01	18.67	378.8	32.03	5.650	85.19	20.71	14.45	272.4	26.83	23.28	482.1	38.51
1.714	23.57	19.63	10.54	179.5	23.32	19.22	392.4	32.82	6.131	93.55	20.90	14.86	282.8	27.24	23.71	490.4	39.12
2.200	30.58	19.73	10.88	187.6	23.59	19.65	402.6	33.40	6.692	103.6	21.11	15.33	294.6	27.82	24.02	496.4	39.59
2.654	37.26	19.82	11.31	197.1	23.94	20.14	414.3	34.11	7.041	109.9	21.31	15.81	306.5	28.34			
3.223	45.84	19.94	11.84	209.3	24.36	20.69	426.5	34.86	7.480	118.1	21.53	16.28	318.8	28.94			

pressure regions where the measurements of viscosity were made by Schlumpf et al. (1975) and in this study are shown in Figure 1. The experimental results are given in Table 2 and Figures 2 and 3. The density values given in Table 2 were calculated from the interpolation of the compressibility data reported by Couch et al. (1961). The dotted lines in Figure 2 show the experimental data reported by Schlumpf et al. (1975).

The viscosity at normal pressure, η_1, can be expressed as a function of the temperature, T, as

Table 3. Viscosity of Nitrous Oxide at Normal Pressure

T/K	η/μPa·s	dev[a]/%	ref	T/K	η/μPa·s	dev/%	ref
298.16	14.98	0.87	Fisher (1909)	635.95	28.75	−0.67	Raw and Ellis (1958)
299.36	15.17	1.78		684.75	31.29	1.91	
348.96	17.39	0.99		739.85	32.63	0.03	
414.76	19.70	−2.22		793.15	33.95	−1.35	
456.26	21.61	−1.38		298.15	14.86	0.08	Chakraborti and Gray (1965)
497.56	23.48	−0.58		308.15	15.38	0.38	
563.06	26.10	−0.40		353.15	17.30	−0.63	
686.76	30.73	−0.14		196.8	9.86	0.28	Harris et al. (1979)
273.10	13.62	−0.16	Vogel (1914)	200.9	10.06	0.18	
300.05	14.88	−0.39	Trautz and Kurz (1931)	213.2	10.65	−0.16	
350.05	17.26	−0.22		240.6	12.00	−0.36	
400.05	19.43	−0.39		276.7	13.78	−0.27	
450.05	21.58	−0.34		300.7	14.96	−0.06	
500.05	23.55	−0.70		328	16.43	1.09	Kestin and Wakeham (1979)
550.05	25.55	−0.59		368	18.28	1.09	
185.20	9.243	0.06	Johnston and McClosky (1940)	418	20.64	1.74	
201.17	10.062	0.07		473	23.04	1.90	
215.54	10.766	−0.18		372	18.48	1.19	Clifford et al. (1981)
229.94	11.487	−0.21		470	22.53	0.20	
245.00	12.186	−0.62		571	26.53	0.07	
259.97	12.948	−0.41		667	30.45	1.26	
273.28	13.616	−0.25		733	34.38	1.89	
285.77	14.214	−0.29		298.15	14.90	0.35	this work
300.10	14.891	−0.33		323.15	16.00	−0.17	
300.15	14.897	−0.31		348.15	17.13	−0.30	
429.15	20.66	−0.51	Raw and Ellis (1958)	373.15	18.30	−0.07	
530.05	24.84	−0.30		398.15	19.41	−0.06	
582.15	26.39	−2.03					

[a] Dev [%] = $100(\eta_{exp} - \eta_{cal})/\eta_{cal}$.

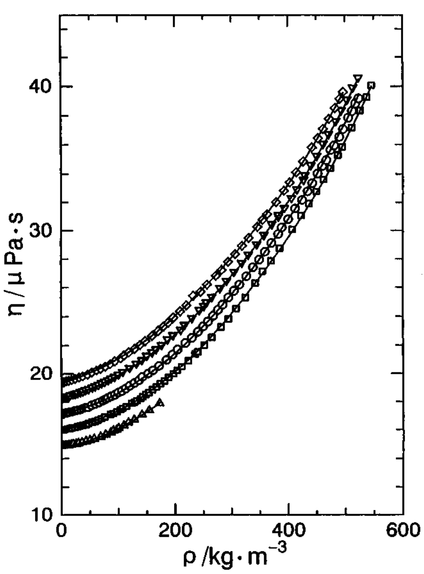

Figure 3. Plots of viscosity η as a function of density ρ for nitrous oxide. Symbols are the same as in Figure 2.

$$\eta_1/\mu\text{Pa·s} = (T/\text{K})^{0.5}/(a_1 + a_2/(T/\text{K}) + a_3/(T/\text{K})^2 + a_4/(T/\text{K})^3) \quad (1)$$

where a_i was the constant in eq 1 ($i = 1-4$) and $a_1 = 0.5992$, $a_2 = 0.1770 \times 10^3$, $a_3 = -0.2413 \times 10^4$ and $a_4 = -0.7192 \times 10^6$. The deviations of experimental viscosity values at normal pressure from the calculated values with eq 1 are shown in Table 3. The average and maximum deviations of the previous data given in Table 3 from eq 1 were ±0.63% and ±2.22%, and those of the data obtained in this study were ±0.19% and ±0.35%, respectively.

The viscosity data under high pressure were compared with those calculated values from Chung's correlation (1988) and Lee−Thodos' correlation (1988), and the deviation plots are shown in Figures 4 and 5, respectively. The

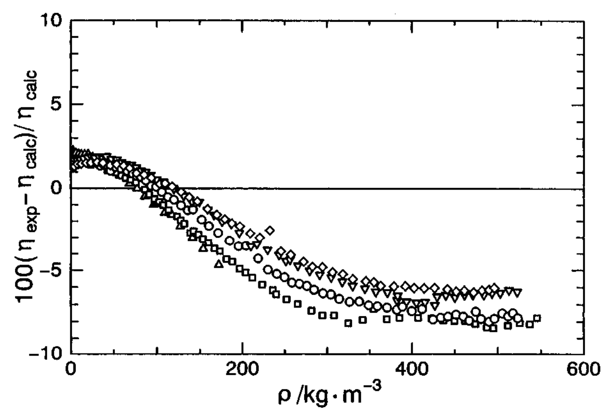

Figure 4. Deviation of experimental viscosity from Chung's equation (1988). Symbols are the same as in Figure 2.

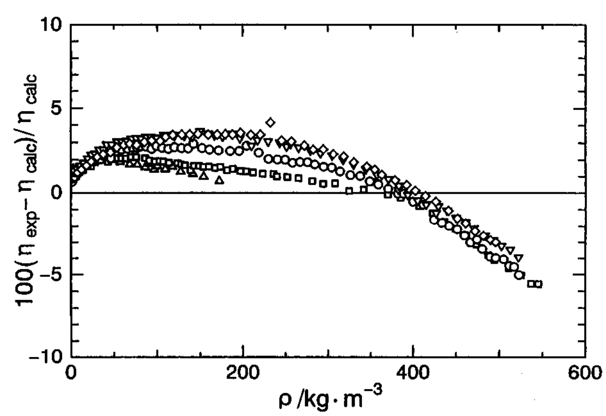

Figure 5. Deviation of experimental viscosity from Lee-Thodos' equation (1988). Symbols are the same as in Figure 2.

deviation from the Lee-Thodos correlation was found to be smaller than that from the Chung correlation.

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