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THE VISCOSITY OF ARGON, NITROGEN AND AIR AT PRESSURES UP TO 800 KG/CM²

By Tadashi Makita*

The recent survey of available data concerning the viscosity of gases, which was carried out by Hilsenrath and Touloukian[1], reveals that accurate data on the viscosity of gases at the wide region of pressure and temperature are still very scarce. The present investigation has been undertaken to obtain some new values of the viscosity of argon, nitrogen and air at the extended conditions of pressure and temperature. That is, the measurement of the viscosity is made under pressures up to 800 kg/cm² at 25, 50, 75, 100 and 150°C for argon, and at temperatures up to 200°C for nitrogen and air, by a rolling-ball method described previously[2].

On the viscosity of argon, Kiyama and Makita[3] determined first by a rolling-ball method under pressures up to 100 kg/cm² at five different temperatures: 50, 100, 150, 200 and 300°C. Recently, Kestin and Pilarczyk[4] used an oscillating-disk viscometer and measured the viscosity of argon up to 70 atm at 20°C, and Michels, Botzen and Schuurman[5], who used a transpiration method, covered the range of up to about 2000 atm at 25, 50 and 75°C.

The effect of pressure on the viscosity of nitrogen was carefully determined by Michels and Gibson[6] under pressures up to 970 atm at 25, 50 and 75°C, using a transpiration method. And H. Iwasaki[7] measured it by an oscillating-disk method under pressures up to about 200 atm at 25, 100 and 150°C, and Kestin and Pilarczyk[4] also determined it at 1~70 atm and 21°C.

Finally, on the viscosity of air, I. F. Golubev[8] used a transpiration method and covered the range of pressures up to 300 kg/cm² at four different temperatures: 0, 16, 50 and 100°C; H. Iwasaki[9] determined it at pressures up to about 200 atm and three different temperatures: 50, 100 and 150°C; and recently Kestin and Pilarczyk[4] measured it under pressures up to 70 atm at 21°C.

Experimentals

The apparatus and its experimental procedure were described in details in the previous paper[2]. In the measurement of the viscosity of air at 150 and 200°C, the contact surfaces of the electrodes are covered by platinum in order to prevent them from oxidation.

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1) J. Hilsenrath and Y. S. Touloukian, *Trans. ASME*, 76, 967 (1954)
2) R. Kiyama and T. Makita, *This Journal*, 26, 70 (1956)
3) R. Kiyama and T. Makita, *ibid.*, 22, 49 (1952)
4) J. Kestin and K. Pilarczyk, *Trans. ASME*, 76, 987 (1954)
5) A. Michels, A. Botzen and W. Schuurman, *Physica*, 20, 1141 (1954)
6) A. Michels and R. O. Gibson, *Proc. Roy. Soc. London*, 134 A, 288 (1931)
7) H. Iwasaki, *Bull. Chem. Research Institute of Non-aqueous Solutions*, 3, 117 (1953)
8) I. F. Golubev, *J. Tech. Phys. USSR*, 8, 1932 (1938)
9) H. Iwasaki, *Bull. Chem. Research Institute of Non-aqueous Solutions*, 1, 27 (1951)

The argon and nitrogen used in this measurement have been obtained from commercial sources and are not further purified. The purities of argon and nitrogen as indicated by the manufacturers are 99.9% and 99.8%, respectively.

The values of the density of gases which are necessary for the calculation of the viscosity have been obtained from the compressibility data of A. Michels, Hub. Wijker and Hk. Wijker[10] for argon, and of E. H. Amagat[11] for nitrogen and air.

Results and Considerations

The present results of argon are given in Fig. 1, where the values of Michels *et al.* at 25, 50 and 75°C and of Kestin *et al.* at 20°C are also plotted. Although the values of Michels *et al.*

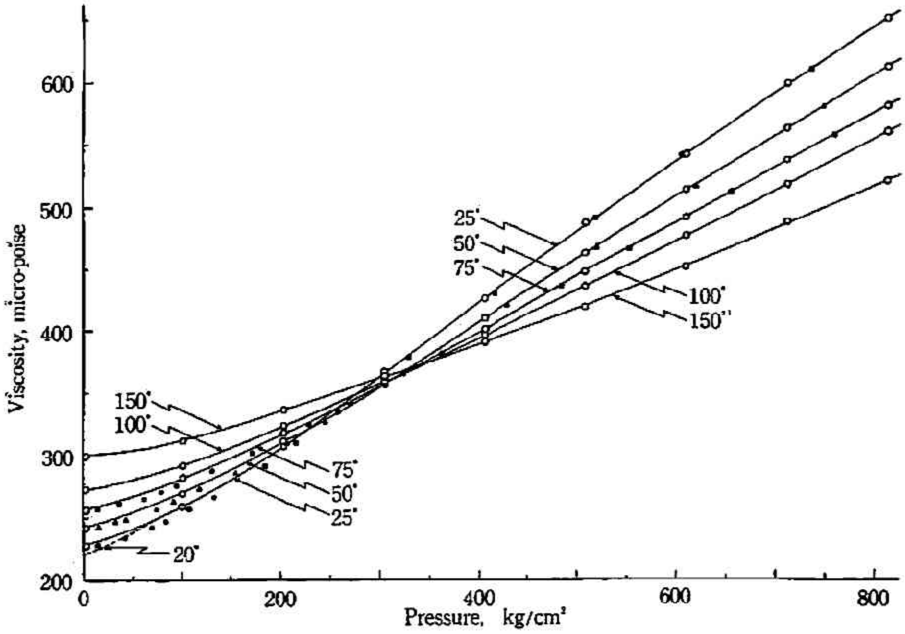

Fig. 1 Viscosity isotherms of argon
—O—: Author, -----: Kestin and Pilarczyk,
●: 25°C, ▲: 50° and ■: 75°C of Michels *et al.*

under pressures lower than 200 kg/cm² are smaller by about 2% than the present ones, the good agreement is found between both under pressures higher than 300 kg/cm² at the three temperatures. The values of Kestin *et al.* are not comparable with the present ones because of the difference in temperature, but it seems that the value at 70 kg/cm² of Kestin *et al.* is larger. Finally, the present values under 100 kg/cm² agree with the previous ones within the experimental error, as considered in the case of oxygen[2]. There are no comparative values under pressures higher than

10) A. Michels, Hub. Wijker and Hk. Wijker, *Physica*, **15**, 627 (1949)
11) E. H. Amagat, *Ann. chim. phys.*, **29**, 68 (1893)

100 kg/cm² at 100 and 150°C.

The present results of the viscosity of nitrogen are plotted in Fig. 2, in which the values

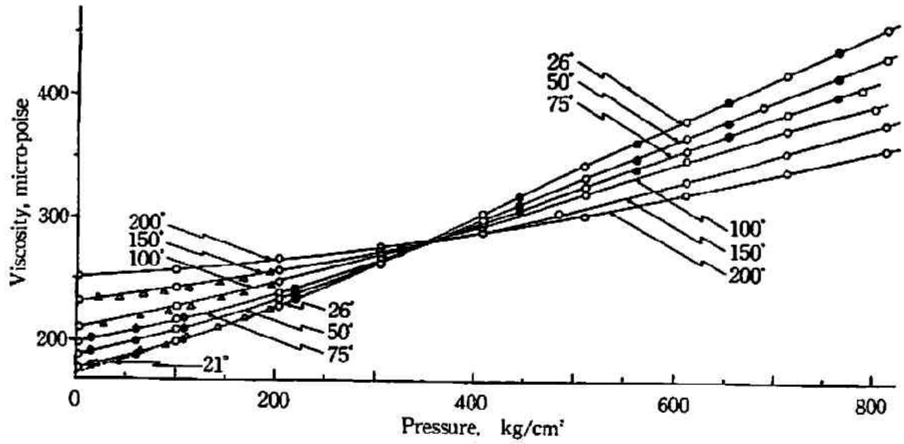

Fig. 2 Viscosity isotherms of nitrogen
—O—: Author, -----: Kestin and Pilarczyk,
●: 25, 50 and 75°C of Michels and Gibson,
△: 25, 100 and 150°C of H. Iwasaki.

of Michels *et al.* at 25, 50 and 75°C, Iwasaki's at 25, 100 and 150°C, and the data of Kestin *et al.* at 21°C are also plotted. The values of Michels *et al.* agree very well with the present results as described previously[2]. The agreement between Iwasaki's data and the present ones is also good at 25°C, but the former are smaller at both 100 and 150°C. It seems that the value at 70 kg/cm²

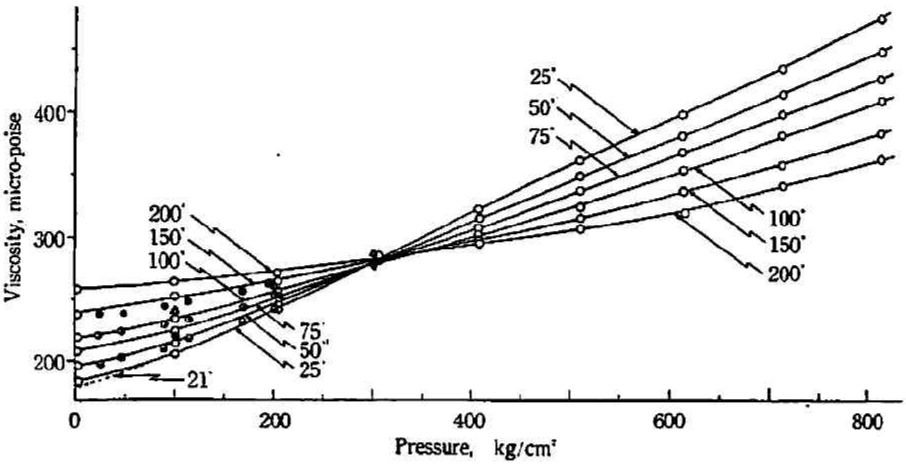

Fig. 3 Viscosity isotherms of air
—O—: Author, -----: Kestin and Pilarczyk,
◆: 50° and △: 100°C of I. F. Golubev,
◒: 50°, ◑: 100° and ●: 150°C of H. Iwasaki.

of Kestin *et al.* is larger as mentioned in the case of argon. No comparative data on the effect of pressure upon the viscosity of nitrogen at 200°C have been traced.

The results of air are given in Fig. 3, where Golubev's values at 50 and 100°C, Iwasaki's at 50, 100 and 150°C, and the data of Kestin *et al.* at 21°C are also plotted. The present isotherms of 50 and 100°C lie between Golubev's and Iwasaki's ones, Golubev's values being larger by about 2~3% than the present ones, and Iwasaki's data at 150°C are also smaller. It seems that the value of Kestin *et al.* is larger at 70 kg/cm². No comparative values under pressures at 200°C have been reported.

The smoothed values which have been read from these isotherms are given in Table 1, where the values of the National Bureau of Standards, USA[12], at the ordinary pressure are also tabulated.

To conclude these results, it can be seen that the effect of pressure upon the viscosity of gases is always positive at a certain temperature, and that the viscosity at low temperatures increases with pressure more rapidly than at higher temperatures. Therefore, the isotherms cross each other as seen in these figures, that is, the temperature coefficient of the viscosity at constant pressure, $(\partial\eta/\partial T)_p$, is positive at low pressures as is the normal case for gases and becomes smaller with

Table 1 Smoothed values of viscosity in micro-poise

Temperature \ Pressure	1 atm	100	200	300	400	500	600	700	800
				kg/cm²					
				ARGON					
25°C	228 (288)	258	305	362	422	482	537	593	645
50	243 (243)	271	310	354	406	458	510	558	608
75	258 (258)	282	317	355	398	445	489	533	577
100	273 (272)	292	323	357	394	433	473	515	556
150	300 (299)	312	336	362	389	417	450	484	518
				NITROGEN					
26	177 (178)	199	228	263	302	341	379	416	452
50	189 (189)	209	233	262	297	331	364	398	430
75	199 (199)	217	238	266	295	325	355	385	413
100	211 (209)	228	248	270	293	319	346	372	394
150	231 (229)	243	257	273	289	309	330	353	376
200	251 (248)	258	266	277	289	303	320	339	357
				AIR					
25	185 (184)	207	241	281	321	359	397	434	472
50	197 (195)	216	246	280	313	346	379	413	446
75	208 (206)	225	251	279	305	334	365	395	425
100	219 (217)	234	256	279	300	325	351	379	407
150	238 (238)	251	265	281	297	315	335	359	382
200	257 (257)	264	273	283	294	307	321	340	362

The parenthesized values are calculated from the tables of the National Bureau of Standards.

12) U. S. Department of Commerce, National Bureau of Standards, *Tables of Thermal Properties of Gases*, pp. 69, 128, 357, Washington (1955)

increasing pressure, and its sign is converted at the crossing point from positive to negative as is common for liquids. And the pressure of the inversion point of the sign of $(\partial\eta/\partial T)_p$ becomes higher with increasing temperature. If the viscosity is plotted against the density, the isotherms at different temperatures do not intersect and $(\partial\eta/\partial T)_\rho$ remains practically constant over the whole range of the density for the three gases, and the diagram for nitrogen is given in Fig. 4.

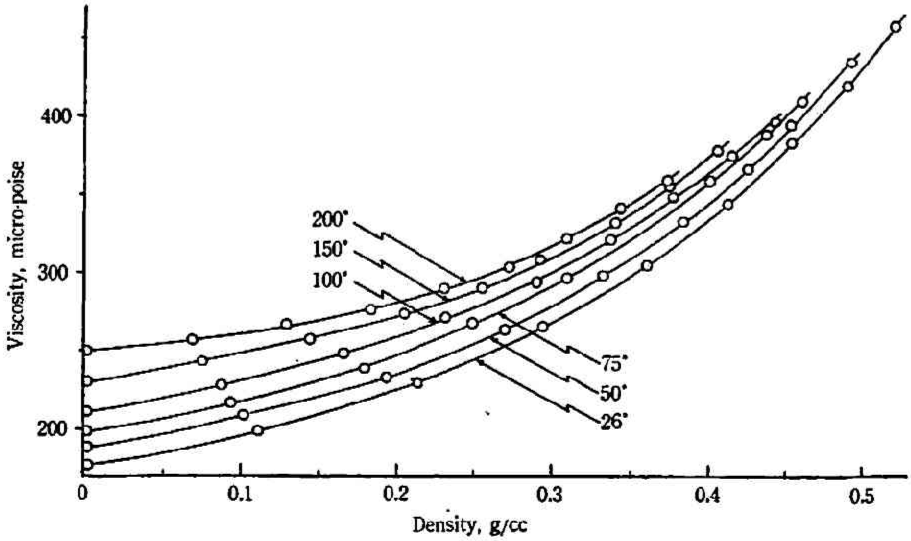

Fig. 4 Viscosity versus density diagram of nitrogen

A Correlation of the Viscosity under Pressures

The results of the present measurement are summarized and correlated by means of the principle of corresponding states. The viscosity coefficients are reduced by their limiting values at low density. For most gases it is satisfactory to take the value of the viscosity at 1 atm to be the limiting value at zero pressure, since the coefficient of viscosity is relatively independent of pressure at low density. In this case the reduced viscosity is defined as $\eta^*=\eta_p/\eta_1$, where η_p and η_1 are the viscosity coefficients under high pressure and 1 atm, respectively, at a certain temperature. According to the principle of corresponding states, this reduced viscosity is a function of the reduced pressure P_r and the reduced temperature T_r.

The present values of the viscosity of argon, nitrogen, air and oxygen[2] have been plotted as isobars of P_r on η^*-T_r diagram, and it is found that these isobars can reproduce all the experimental points within the deviation of 5%. Comings, Mayland and Egly[13] published a generalized viscosity chart based on the similar principle, and covered the region of $P_r=0.1\sim10$ and $T_r=0.8\sim3.0$. In the present investigation the region is extended up to $P_r=25$ and $T_r=4.0$. Furthermore, the reduced viscosity has been calculated and plotted by the following data: argon (1000~

13) E. W. Comings, B. J. Mayland and R. S. Egly, *Univ. Illinois Eng. Expt. Station Bull. series* 354 (1944)

2000 atm at 0, 25, 50 and 75°C)[5], hydrogen (1~1000 atm at 25, 50, 75, 100 and 125°C)[14], and nitrogen-hydrogen mixtures (1~200 atm at 50 and 100°C)[7], covering the region up to $P_r=40$ and $T_r=10$. The generalized viscosity chart obtained is given in Fig. 5, where the reduced

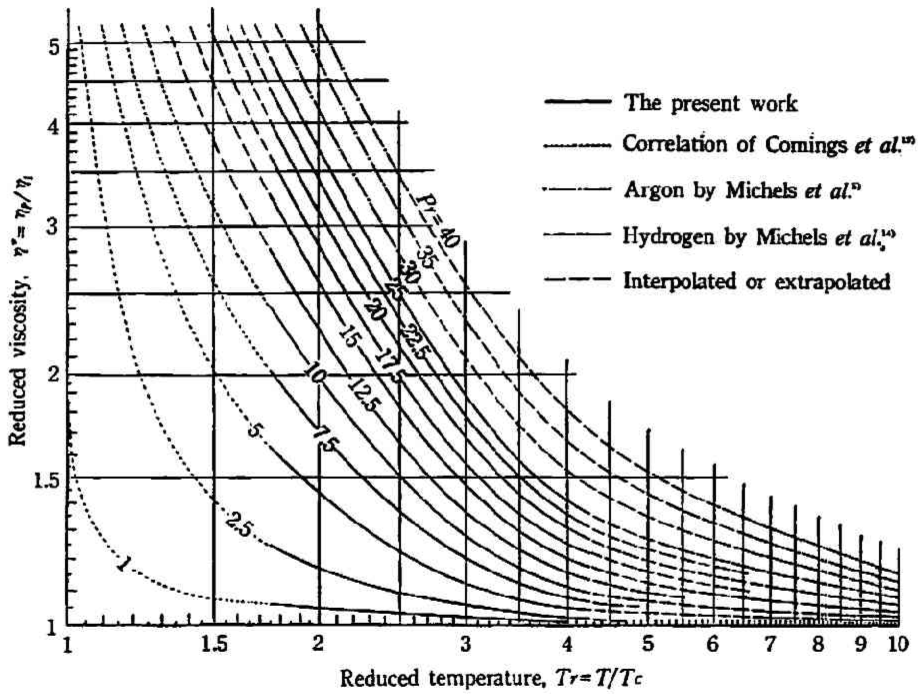

Fig. 5 Generalized correlation chart for the viscosity of gases

viscosity η^* is shown as a function of the pressure P_r and temperature T_r. This chart provides a practical method of predicting the viscosity of gases under conditions where no data exist or no satisfactory theoretical treatments may be applied.

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14) A. Michels, A. C. J. Schipper and W. H. Rintoul, *Physica*, **19**, 1011 (1953)