The Review of Physical Chemistry of Japan Vol. 26 No. 2 (1956)

AN IMPROVED VISCOMETER FOR COMPRESSED GASES AND THE VISCOSITY OF OXYGEN

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In the previous papers[1,2,3] a rolling-ball viscometer for compressed gases was constructed and calibrated using carbon dioxide, and the viscosity of several gases was measured at pressures up to 100 kg/cm^2 and temperatures up to 300°C. The viscometer used in the previous experiments has been partly improved so as to withstand higher pressures and to have higher accuracy, and the viscosity of oxygen is determined under the extended pressure ranges: up to 800 kg/cm^2 at 25°, 500 kg/cm^2 at 50°, 400 kg/cm^2 at 75°C and 300 kg/cm^2 at 100°C.

Apparatus and Experimental Procedure

The equipment, which was described in details in the previous papers, is revised to permit the measurement under higher pressures. The viscometer-tube made of glass is replaced by a tube of non-magnetic 18-8 chromium-nickel steel, which is 250 mm long, 25 mm in outer diameter and about 8 mm in inner diameter. The inner surface of the tube has been carefully finished to be smooth for the ball rolling. The upper and lower ends of the tube are fitted with the insulated electrodes of the same material as the tube for measuring the rolling time of the viscometer-ball, which is permitted to roll within the inclined tube. The tube is connected with the accessary parts and is set in a thermostat, in which an electric magnet for returning the ball to the upper end of the tube is equipped, and also the equipment connected is fixed on a base that can be inclined to any desired angle.

Two electrodes and the tube are connected with a circuit that is led to an audio-oscillator and an amplifier. The electrical system is adjusted that 800 cycle oscillating current less than 0.1 mA may be conducted in the circuit when the ball is contacted with one of the electrodes. The time of the ball rolling between the upper and the lower electrodes is measured as the rolling time.

For operation, the sample gas is introduced into the evacuated viscometer-tube from a gas-reservoir or a pressure-intensifier. At a desired temperature and pressure, the ball is brought to contact with the upper electrode and permitted to roll. The

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[1] R. Kiyama and T. Makita, *This Journal*, 21, 63 (1951)

[2] R. Kiyama and T. Makita, *ibid.*, 22, 49 (1952)

[3] T. Makita, *ibid.*, 24, 74 (1954)

rolling time of the ball is repeatedly measured at several angles of the inclination of the tube.

The dimension of the viscometer at 25°C is as follows:

inner diameter of the tube,	$D=8.031$ mm,
diameters of the balls,	$d=7.928\sim7.948$ mm,
distance of the ball rolling,	$L=185.53$ mm,
inclination angles of the tube,	$\theta=6°53'\sim8°30'$,
density of the ball,	$\rho_B=7.756$ g/cc.

Determination of Viscosity

As described in details and confirmed experimentally in the previous paper[1], there is a definite correlation between the following two dimensionless quantities:

$$\left.\begin{aligned} &\text{resistance factor,} \quad f=\frac{5}{42}\pi g\frac{(D+d)^2}{L^2 d}\cdot\frac{\rho_B-\rho}{\rho}\cdot Z^2\cdot\sin\theta, \\ &\text{Reynolds' number,} \quad Re=\frac{Ld^2}{D+d}\cdot\frac{\rho}{\eta Z}, \end{aligned}\right\} \qquad (1)$$

where g=acceleration of the gravity, ρ=density of gas, η=viscosity of gas and Z= rolling time of the ball. Corrections are required due to the temperature and pressure effect upon the diameters, D and d. The change of diameters with temperature is corrected by using the coefficients of thermal expansion of the materials. The pressure effect is also calculated from the following equations[4]:

$$\left.\begin{aligned} &\text{change of diameter of the tube,} \quad \Delta D=\frac{D_o P}{E}\;\frac{(1+\sigma)R_o^2+(1-\sigma)D_o^2}{R_o^2-D_o^2}, \\ &\text{change of diameter of the ball,} \quad \Delta d=\frac{d_o P}{E}\;(1-2\sigma), \end{aligned}\right\} \qquad (2)$$

where P= internal pressure, E=Young's modulus, σ=Poisson's ratio, R=outer diameter of the tube, and the subscript o shows the diameters at 1 atm and a desired temperature. The changes in the diameters of the tube and ball do not affect on the slope of f-Re correlation curves, but on the location of them, as shown experimentally by Hubberd and Brown[5].

Using the balls of the various diameters, when the f-Re correlation curves for the present viscometer have been drawn from the values of carbon dioxide under pressures up to 100 kg/cm^2 at 20 and 40°C[6], a relation is found in the turbulent region of Re=200~450 as follows:

$$\log f=-0.4830\log Re+K, \qquad (3)$$

where it is found that the apparatus constant K is a function of the diameter ratio, d/D, and within the range of d/D=0.986~0.990 the results are shown in Fig. 1.

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[4] D. M. Newitt, *The Design of High Pressure Plants and Properties of Fluids at High Pressures*, London (1940)

[5] R. M. Hubberd and G. G. Brown, *Ind. Eng. Chem., Anal. Ed.*, **15**, 212 (1943)

[6] H. Stakelbeck, *Z. ges. Kälte-Ind.*, **40**, 33 (1933)

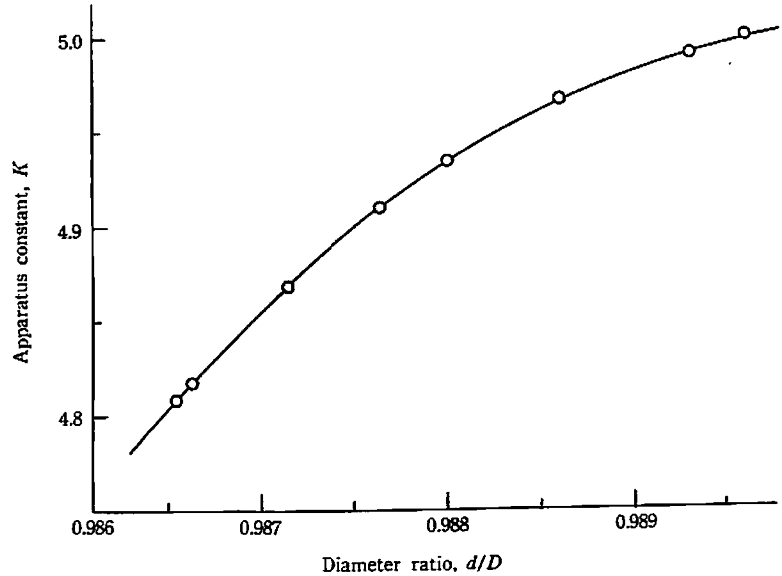

Fig. 1 Apparatus constant of the viscometer as a function of diameter ratio

Table 1 Comparison of the present values of nitrogen with the values of Michels and Gibson[7], in micro-poise

Pressure kg/cm^2	26°C		50°C		75°C	
	Authors	M & G(25°)	Authors	M & G	Authors	M & G
100	199	199	209	207	217	216
200	228	230	233	232	238	237
300	263	265	262	263	266	265
400	302	303	297	298	295	295
500	341	341	331	331	325	324
600	379	378	364	362	355	353
700	416	416	398	394	385	382
800	452	451	430	427	413	412

The values of Michels and Gibson are read from the isotherms which have been drawn by plotting their values on the viscosity-pressure diagram.

Therefore, if d/D is known at a desired temperature and pressure, K is read from Fig. 1, and the viscosity η is evaluated in the turbulent region by measuring Z and $\sin\theta$ and using Eqs. (1) and (3).

Reliability of this method of evaluating the viscosity has been experimentally checked by the values of nitrogen of Michels and Gibson[7]. And the results are shown in Table 1, where the scattering of the evaluated values at each experimental

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7) A. Michels and R. O. Gibson, *Proc. Roy. Soc., London,* **A134**, 288 (1931)

point does not exceed 1.5%. It can be seen in this table that the satisfactory agreement exists between the values of Michels *et al.* and those of the present experiment over the whole region of pressure and temperature.

Viscosity of Oxygen

The oxygen used in this measurement has been obtained from a commercial source and is not further purified. The purity is more than 99.8% as indicated by the manufacturer.

The values of the density of oxygen have been calculated from the compressibility data of E. H. Amagat8).

As the chromium-nickel steel electrodes are oxidized in the measurement of the viscosity of oxygen at the temperatures higher than 50°C, the contact surfaces of the electrodes are covered with platinum in order to prevent them from oxidation. Nevertheless, the measurement has been made impossible under pressures higher than 500 kg/cm^2 at 50°, 400 kg/cm^2 at 75° and 300 kg/cm^2 at 100°C, where it is found that fine brownish rust has been formed on the surface of the steel ball.

The present results of the viscosity of oxygen are plotted as the isotherms in Fig. 2. It can be seen that the effect of pressure on the viscosity of oxygen is positive at a certain temperature, and that the viscosity at low temperatures increases with pressure more rapidly than at higher temperatures.

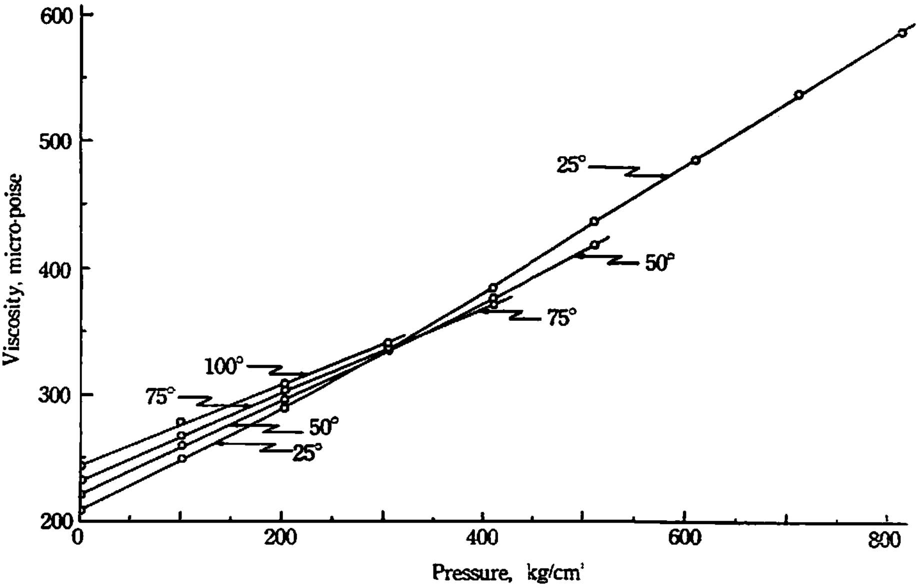

Fig. 2 Viscosity isotherms of oxygen

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8) E. H. Amagat, *Ann. chim. Phys.*, **29**, 68 (1893)

Table 2 Smoothed values of the viscosity of oxygen in micro-poise

Pressure / Temperature	1 atm	kg/cm^2							
		100	200	300	400	500	600	700	800
25°C	208 (206)	248	289	333	381	430	481	532	583
50	221 (219)	259	297	334	378	420			
75	232 (231)	268	303	336	372				
100	244 (243)	279	309	340					

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

The present values under 100 kg/cm^2 agree with the previous ones within the experimental error**. No comparative data under pressures higher than 100 kg/cm^2 have been reported. The values at the atmospheric pressure agree within 1% with those calculated by interpolation from "Tables of Thermal Properties of Gases"[9], as shown in Table 2. The smoothed values which have been read from the isotherms are also given in Table 2.

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** In the previous experiments, as the ratio d/D was smaller (d/D=0.966~0.974) than the present one, the accuracy became lower with increasing pressure and the maximum deviation in the evaluated viscosity amounted to about 3.5% at 100 kg/cm^2.

9) U. S. Department of Commerce, National Bureau of Standards, *Tables of Thermal Properties of Gases*, Washington, p. 424 (1955)