A NEW SIMPLE VISCOMETER FOR COMPRESSED GASES AND VISCOSITY OF CARBON DIOXIDE.

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Although the effect of pressure upon the viscosity of several gases has been reported by many investigators[1], their data failed to cover the wide region of the pressure and temperature of gases. In this investigation, a new viscometer for compressed gases, which is simple and suitable for rapid measurement, is constructed and the viscosity of carbon dioxide is determined at the pressures from 10 to 60 kg/cm^2 and the temperatures between 50 and 300°C.

New viscometer for compressed gases.

For the determination of the viscosity of gases, various methods[1] have been reported, in which the "rolling-ball method"[2] is chosen as the most suitable for the wide region of the pressure and temperature with the following reasons; 1) the apparatus can be extremely simple, 2) only a small sample is required, 3) the procedure of measurement is simple and rapid, 4) the system possesses great flexibility, being capable of changing one or more of variables: the diameters of the tube and the ball, the angle of inclination, and the roll distance. Furthermore, according to the result of the test of the strength of glass-tube[3], visual observation of ball rolling at constant velocity in a glass-tube and the elimination of the inaccuracy from the accelerated motion of the ball in the steel tube[4,5] are possible.

Details of the viscometer.

Viscometer-tube. In this investigation soda-glass is used; if necessary, pyrex- and silica-glass may be used. The tube needs to be circular in the bore, equal diameter over the whole length, and smooth inner surface. The worked and annealed glass-tube has no strain[3]. These treated tubes, which are 5.5~6.0 mm in

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1) R. Kiyama, "Physico-chemical constants of gases under high pressure" (Japanese), p. 29 (1950) Tokyo. (Special Ed. series No. 2 of "*J. of Ammonium Sulphate Engineering*.")
2) R. Wobser and F. Müller, *Kolloid-Beihefte*, 52, 165 (1941)
3) R. Kiyama and K. Inoue, *This Journal*, 21, 73 (1951)
4) A. S. Smith and G. G. Brown, *Ind. Eng. Chem.* 35, 705 (1943)
5) L. B. Bicher and D. L. Katz, *ibid.*, 754 (1943)

inside diameter and 8.5～9.0 mm in outer diameter, can bear with 240 kg/cm^2 of inner pressure. The viscometer-tube is connected with the steel system by the self-sealing method[3].

Viscometer-ball. The smooth and completely spherical steel-ball corresponding to the diameter of the tube is used. The diameter ratio of the tube to the ball is between 1.015 and 1.025. The ball is brought to a definite position by means of an electric magnet.

Thermostat. The viscometer-tube is set in an electrical-heating thermostat, the temperature of which is regulated within 0.1°C. The window for visual observation is made over the whole length of the thermostat.

Whole connection. For the introduction of gas into the viscometer-tube and compression of gas, the viscometer is connected as shown in Fig. 1, and the whole connection is fixed on the base that can be inclined to any desired angle. For operation, after the system is evacuated through valve V_1, the sample gas is introduced through the slightly opened valve V_2. In the case of increasing the pressure above the pressure of gas reservior A, the gas is also let into the trap B and compressed by mercury in B′ with the pressure of the oil pump.

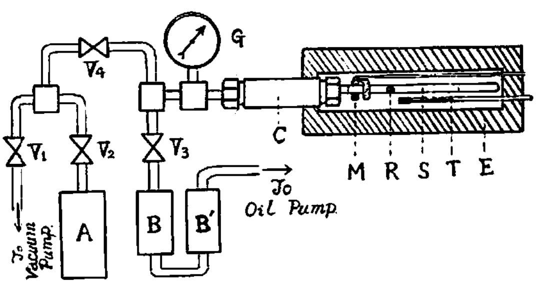

Fig. 1
Schema of high pressure viscometer.
A, Gas reservior; B, Mercury trap; B′, Mercury reservior; C, Connecting steel cylinder; E, Electric thermostat; G, Pressure gauge; M, Magnet; R, Rolling ball; S, Viscometer-tube; T, Thermometer; V_1, V_2, V_3 and V_4, Valves.

Determination of absolute Viscosity.

Viscosity coefficient η has been calculated by the following equation[2,6,7,8];

$$\eta = b \cdot Z \cdot \sin\theta \cdot (\rho_0 - \rho), \qquad (1)$$

in which Z is the roll time, θ is the inclination angle from the horizontal, ρ and ρ_0 are the density of gas and ball, respectively, and b is a constant. Eq. 1 is satisfied only when the flow of gas through the crescent space between the tube and the ball is in the streamline region of flow.

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6) F. Höppler, *Z. tech. Physik*, 4, 165 (1933)
7) B. H. Sage, *Ind. Eng. Chem., Anal. Ed.*, 5, 261 (1933)
8) E. Schröer and G. Becker, *Z. Phys. Chem.*, A173, 178 (1935)

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Hubberd and Brown[9] showed that if the ball is rolling at uniform velocity, there is a certain correlation between the following two quantities;

$$\left.\begin{aligned} &\text{resistance factor,} \quad f=\frac{5\pi g}{42}\cdot\frac{(\mathrm{D}+\mathrm{d})^2}{\mathrm{L}^2\mathrm{d}}\cdot\frac{\rho_0-\rho}{\rho}\cdot Z^2\cdot\sin\theta, \\ &\text{Reynolds number,} \quad \mathrm{Re}=\frac{\mathrm{Ld}^2}{\mathrm{D}+\mathrm{d}}\cdot\frac{\rho}{\eta Z}, \end{aligned}\right\} \qquad (2)$$

in which g is the acceleration of gravity, D and d are the diameters of the tube and the ball, respectively, and L is the roll distance. If f is plotted against Re on the logarithm scale, a straight line with the slope of -1.0 is obtained when the flow is in the streamline region. This line is no longer straight where the flow is changing from the streamline region to the turbulent one, but curves until it reaches a certain smaller slope in the turbulent region. This f–Re correlation is obtained from measuring the roll time of the ball and the inclination angle of the viscometer using the viscosity-known gases, and is used to compute the viscosities of other gases from the roll time and inclination angle.

Experimental results.

The correlation curve between f and Re is drawn by measuring Z and θ of gases of known viscosity in various conditions, and used for testing this viscometer.

Effect of inclination angle. Changing the inclination angles between 0°35′00″ and 3°54′20″, the atmospheric air free from moisture and carbon dioxide is used at 20°C, and the results are plotted in Fig. 2. All points are in the streamline region of flow and lie on the straight line of the slope of -1.0. Since η, ρ, ρ_0, and b are constant in this measurement, the following relation is obtained from Eq. 1;

$$Z\cdot\sin\theta=\text{const.} \qquad (3)$$

This relation is satisfied whithin

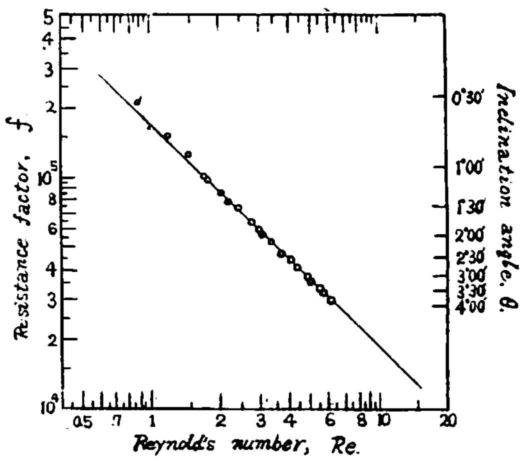

Fig. 2
f–Re correlation. Effect of inclination angle between 0°35′0″ and 3°54′20″ at 20°C. (Tube-No. 9)
D=0.6145 cm d=0.6005 cm L=12.566 cm

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

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1% except θ less than 1°.

Effect of temperature. The effect of temperature is not seen upon the correlation between f and Re, if D, d, ρ and ρ_0 at the measuring temperature are calculated from their coefficients of thermal expansion. At the temperatures between 20 and 300°C, the air and carbon dioxide* under the atmospheric pressure are used for measurement at various angles between 1°30′ and 3°30″. The correlation between f and Re is satisfied within 1% all over temperatures.

Effect of pressure. In order to obtain the correlation between f and Re with increasing pressure, carbon dioxide is used at the pressures from 1 up to 60 kg/cm² and the temperatures of 20, 30 and 40°C, where the viscosity of carbon dioxide is known[10] and the values of density are calculated from the compressibility data of Michels[11] and Amagat[12]. The results obtained are shown in

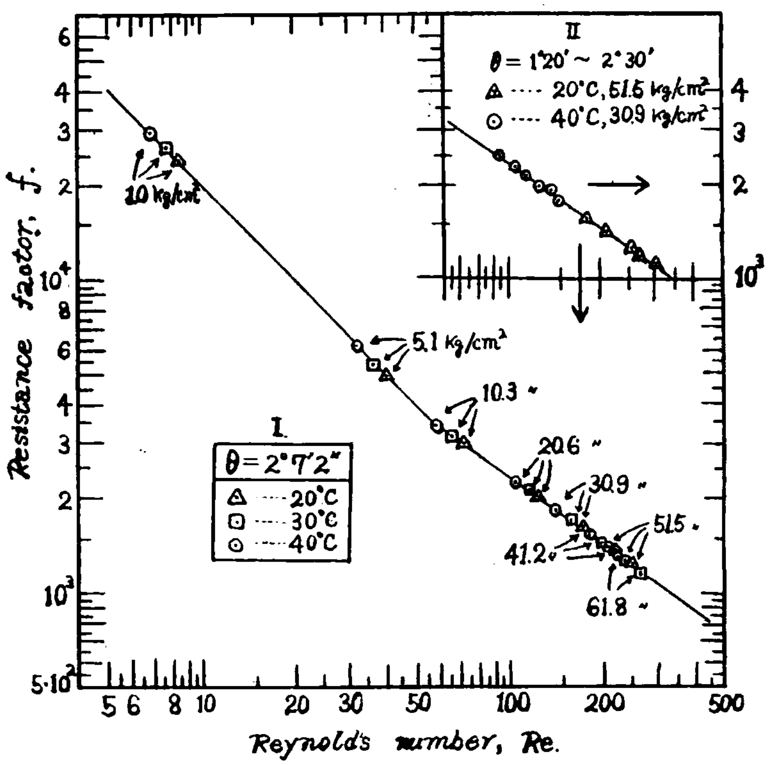

Fig. 3
f-Re correlation. Effect of pressure. (Tube-No. 1)
D=0.5671 cm d=0.5548 cm L=9.9340 cm (20°C)

* Purity of carbon dioxide used in this report is 99.8%.

10) H. Stakelbeck, *Z. ges. Kälte-Ind.*, 40, 33 (1933)

11) A. Michels and C. Michels, *Proc. Roy. Soc., London*, A153, 201, 215 (1936)

12) M. Amagat, *Ann. chim.*, 29, 68, 505 (1893)

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Fig. 3. With increasing pressure of gas, the straight line of slope of −1.0 turns to a line of slope of −0.73, but the scattering of points is not so remarkable in the transition zone between the streamline region to the turbulent flow (maximum deviation is only 3%). The points plotted on curve I in Fig. 3 are measured at a constant angle, $\theta=2°07'02''$, and the points on curve II show the effect of inclination angles between 1°20′ and 2°30′ in the turbulent region. The effect of pressure upon D, d and ρ_0 is negligible within these region of the pressure and temperature. The viscosity of compressed gases can be measured within the error of 1.5% except the transition zone between the streamline flow and the turbulent one.

Viscosity of carbon dioxide under pressure.

In several reports[1] on the viscosity of carbon dioxide under pressure, the maximum temperature is only 105°C[13]. In this investigation, the viscosity of carbon dioxide at the temperatures from 50 to 300°C and the pressures up to 60 kg/cm^2 is determined and plotted in Fig. 4. The smoothed values estimated from Fig. 4 are shown in Table 1.

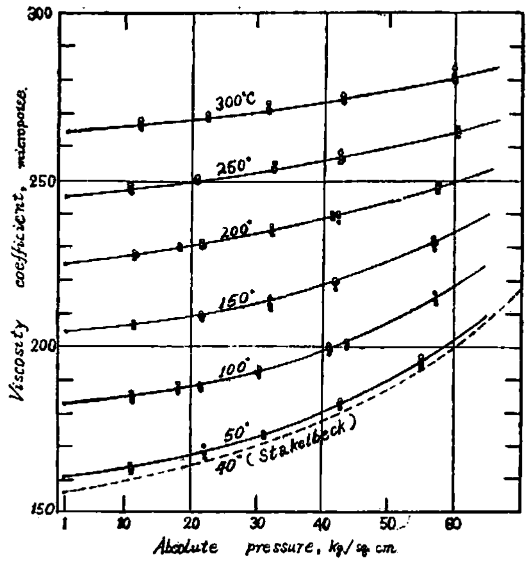

Fig. 4
Viscosity isotherms of carbon dioxide.

13) E. W. Comings, B. J. Mayland and R. S. Egly, *Univ. Illinois Eng. Expt. Sta. Bull.*, series No. 354, 7 (1944)

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Table 1

Smoothed values of the viscosity of carbon dioxide.
(in Micropoise)

Temperature °C	Pressure, (kg/cm^2)						
	1	10	20	30	40	50	60
50	160	163	167	173	180	190	202
100	183	184	187	191	198	207	218
150	205	206	208	211	217	225	235
200	225	227	230	233	238	343	249
250	245	247	249	253	256	260	264
300	264	266	268	271	274	277	281

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