Studies on Fluorine at Low Temperatures. V. Viscosity of Fluorine Gas at Low Temperatures.

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(Received August 12th, 1937.)

Determination of the size, mean free path, and mean velocity of fluorine molecule, though important in the study of the reaction of fluorine gas, has not yet been made. The present author is now making a study of the reaction velocity of fluorine gas. But prior to this, he determined the viscosity of fluorine, and deduced the above-mentioned constants from it.

I. **Method and Apparatus.** For the determination of viscosity, two methods are available: observation of flow in a capillary tube and that of oscillation-rotation of a disc. In the author's measurements with fluorine, (i) the apparatus had to be as compact as possible for ensuring a constant low temperature, and (ii) mercury could not be used because of the corrosive nature of the gas. For this reason, the author adopted the second method in which decrement of the oscillation-rotation of the disc was measured.

H. Vogel's apparatus(1) was remodelled in some measure. The author's apparatus is illustrated in Fig. 1, where A, B, and C are made of hard glass and they are connected by ground junctions S_1 and S_2. C has a glass cock S_3, around which a platinum filament is wound. The filament is moved upward and downward by turning the cock. B has a window W, and A is fitted with a branch tube D for introducing fluorine and with a device of the oscillating disc E. E, as separately illustrated in details, consists of a, b, and c, where b is the oscillatory rotating disc and is hung from S_3 with a nickel wire N and a platinum wire P, thus lying at equal distances from a and c. Further, a, b, and c are made of nickel-plated brass, and E is set in contact with c on the ground glass

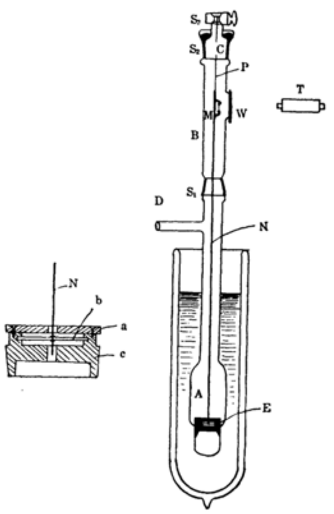

Fig. 1.

(1) Vogel, *Ann. Physik*, **43** (1914), 1235.

surfaces. In B, as illustrated, is a mirror M, whose oscillation-rotation is observed by means of a telescope through W at a distance of 2 metres. The dimensions of the important parts of E are as follows: diameter of the oscillating disc 30 mm., thickness 1.8 mm., weight 10.8 g., weight of the suspended parts 13.1 g., distance of surfaces between a and b or b and c 1.2 mm., and period of oscillation about 10 sec.

The device for winding up the platinum wire lowers the disc when the experiment has been finished or puts the disc in a proper position between a and c when the experiment is about to be made. On being slightly revolved, S_2 gives a moment of revolution to the disc.

Apparatus for maintaining a low temperature and for measuring the temperature are represented in a simple way by Dewar vessels. In practice, however, a thermostat was used, which had been often used in the author's experiments at low temperatures. The temperature was determined by means of a thermocouple made of copper and constantan.

II. **Determination of the Viscosity.** From the ratio of damping of the oscillation of the revolving disc, the viscosity can be determined by the following equation:

$$\eta = \frac{\lambda - K}{\tau c} \qquad (1),$$

where η is viscosity, τ period of oscillation, λ logarithmic decrement of oscillation, K a part of λ, that is, logarithmic decrement due to friction of the parts other than the disc, and c a constant peculiar to the apparatus.

λ and τ in the foregoing equation are obtained by observation using the mirror, scale, and stop-watch. It will be seen that c can be eliminated by the method described below. K is determined by the following somewhat complicated process.

K consists of (i) decrement due to the torsion of the platinum wire, K_1, and (ii) decrement due to friction between the gas and the mirror and other parts, K_2. Namely, $K=K_1+K_2$. K_1 depends upon the tension of the platinum wire and K_2 upon the kind and pressure of gas. In the case of vacuum, $K_2=0$.

When the material and weight of the disc are varied, with its geometrical dimensions being kept unvaried, $K'=K_1'+K_2$.

Since the period of the oscillation, τ, is independent of the temperature nor the kind of gas, but depends upon the apparatus alone, we may put $c\tau=C$.

As, in the case of vacuum, the total decrement λ which is obtained by observation is K_1, K_1 is a magnitude which can be determined by observation. In the case of the author's experiment, $K_1=0.00031$, and $K_1'=0.00034$.

In the case of air, if the viscosity at 0°C. and T are represented by η_0 and η_T respectively, we shall have, from equation (1),

$$C\eta_0 = \lambda-(K_1+K_2) \quad (2), \qquad C'\eta_0 = \lambda'-(K_1'+K_2) \quad (3),$$

$$\eta_0(C-C') = (\lambda-K_1)-(\lambda'-K_1') \quad (4).$$

Similarly,

$$C\eta_T = \lambda_T-(K_1+K_2) \quad (5), \qquad C'\eta_T = \lambda_T'-(K_1'+K_2) \quad (6),$$

$$\eta_T(C-C') = (\lambda_T-K_1)-(\lambda_T'-K_1') \quad (7).$$

From (4) and (7)

$$\frac{\eta_0}{\eta_T} = \frac{(\lambda-K_1)-(\lambda'-K_1')}{(\lambda_T-K_1)-(\lambda_T'-K_1')} \quad (8).$$

In equation (7), K_2 is eliminated, and the terms on the right side are magnitudes each of which can be determined by observation.

If η_0 is given, η_T will be obtained from the foregoing equation.

From (2) and (5), we have

$$\frac{\eta_0}{\eta_T} = \frac{\lambda-(K_1+K_2)}{\lambda_T-(K_1+K_2)} \quad (9).$$

From this equation, we get

$$K_2 = \frac{\eta_0(\lambda_T-K_1)-\eta_T(\lambda-K_1)}{\eta_0-\eta_T} \quad (10).$$

Thus K_2 is finally determined. K_2 is proportional to the square root of the viscosity of gas, that is,

$$K_2 \propto \sqrt{\frac{\eta}{\eta_0}} \quad (11).$$

With the author's apparatus, the decrement obtained in vacuum was $K_1=0.00031$. As to air, K_2 obtained from equation (10) was $K_2=0.00010$. Hence,

$$K = K_1+K_2 = \left(31+10\sqrt{\frac{\eta}{\eta_0}}\right)\times 10^{-5}.$$

If we use λ_0 and K_0 for the logarithmic decrement of air at 0°C., and λ and K for any other gas, with a given apparatus at a given temperature, we shall have

$$\eta = \eta_0 \frac{\lambda - K}{\lambda_0 - K_0} \tag{12}$$

Thus, if the viscosity of air at 0°C. is given, η of any other gas can be deduced from it.

Further, in equation (11), the ratio of λ can stand for the ratio of viscosity. Thus, $K_2 \propto \sqrt{\frac{\lambda}{\lambda_0}}$.

III. **Determination of the Logarithmic Decrement.** Let the reading of a certain leftward movement of the mirror in the course of oscillatory rotation be represented by a and the succeeding rightward movement by b, then $a/b=n$, $\lambda=\log n$.

In practice, the mirror is vibrated several times, and its deflection is observed. The following relation exists:

$$\frac{a_\nu + b_{\nu+1}}{a_{\nu+15} + b_{\nu+16}} = n^{30}, \quad \lambda = \log n = \frac{1}{30} \log \frac{a_\nu + b_{\nu+1}}{a_{\nu+15} + b_{\nu+16}}.$$

IV. **Results of Measurement.** (1) *Air.* The observed values of decrement of oscillation are given in Table 1.

Table 1.

$a_\nu + b_{\nu+1}$	$\log (a_\nu + b_{\nu+1})$	30λ
53.79	1.73070	
43.54	1.63889	
35.49	1.55011	
28.83	1.45984	
23.40	1.36920	
19.03	1.27944	0.45126
15.44	1.18893	0.44998
12.55	1.09864	0.45147
		Average 0.45090

$\lambda_0=1/30\ (0.45090)=0.015030$.

Further, $\tau=11.20$ sec., $\lambda_0-K_0=0.015030-0.00041=0.014620$.

(2) *Hydrogen.* To check the above-mentioned method and apparatus, determination was made with hydrogen gas at various low tem-

peratures. The hydrogen was obtained by electrolysis of water and refined by means of palladium catalyser. The results are given in Table 2.

Table 2.

t	T	p	λ	K	$\eta\times10^7$
0	273.2	764	0.007639	0.00038	856
−102.8	170.5	766	0.005595	,,	615
−181.9	91.3	758	0.003789	,,	402
−194.7	78.5	759	0.003527	,,	371

$$K = K_1 + K_0\sqrt{\frac{\lambda_0'}{\lambda_0}} = 0.00031 + 10\sqrt{\frac{0.007639}{0.01503}} = 0.00038$$

The value of η at 0°C. obtained by the present author is compared with those obtained by other authors in Table 3. The present author's value, though a little too large, may be considered good. (The author adopted $\eta_0 = 1724\times10^{-7}$ for air.)

Table 3.

$\eta\times10^7$	Authors
840	Graham and Meyer
870	Paluj
841	Markowski
850	Volker
849	Vogel
856	Kanda

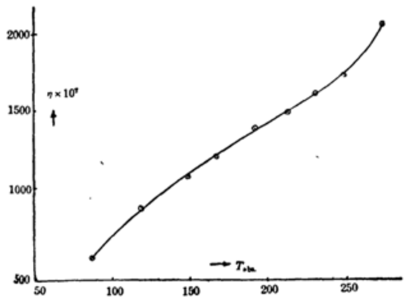

Fig. 2.

(3) *Fluorine.* The results are given in Table 4 and illustrated in Fig. 2.

$$\tau = 11.20\ \text{sec.},\quad \eta_0\,(\text{air}) = 1724\times10^{-7}\,.$$

$$K = 0.00031 + 10\sqrt{\frac{0.01816}{0.01503}} = 0.00042$$

Table 4.

T	p	λ	K	$\eta\times10^{-7}$
273.2	763	0.01816	0.00042	2093
248.9	,,	0.01505	,,	1727
229.6	,,	0.01407	,,	1611
213.1	765	0.01221	,,	1492
192.3	,,	0.01210	,,	1379
167.9	,,	0.01059	,,	1201
148.8	758	0.00957	,,	1080
118.9	,,	0.00783	,,	875
86.8	,,	0.00512	,,	555

V. Determination of the Diameter of Fluorine Molecule, etc. From the foregoing value of the viscosity, we get Sutherland's constant of fluorine, $C=129$.

As for the diameter of the molecule, we have $d=3.02\text{Å}$ from

$$d^2 = 4.56\times10^{-20}\sqrt{M}\Big/\eta_0\left(1+\frac{C}{273.2}\right).$$

Magat[2] obtained $b = 3.4\text{Å}$.

The author got the mean free path

$$L = 9.12\times10^{-6}\text{cm.}\quad\text{from } L=\frac{1}{N\pi\sqrt{2}}\frac{1}{d^2}.$$

In conclusion, the author wishes to express his cordial thanks to Prof. Aoyama who gave him direction and kind guidance throughout this work. The author expresses his heartful thanks to the Japan Society for the Promotion of Scientific Research for a grant.

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(2) Magat, *Z. physik. Chem.*, B, **16** (1932), 1.