The Review of Physical Chemistry of Japan Vol. 22 No. 2 (1952)

# THE VISCOSITY OF CARBON DIOXIDE, AMMONIA, ACETYLENE, ARGON AND OXYGEN UNDER HIGH PRESSURES

By Ryo Kiyama and Tadashi Makita*

In the previous paper[1], a new simple viscometer for compressed gases was reported in detail. Using the viscometer which has been calibrated by H. Stakelbeck's values[2] of carbon dioxide at 20° and 40°C, the viscosity coefficients of several gases are determined at the temperatures from 50 to 300°C and the pressures up to 100 kg/cm².

Several investigations about the effect of pressure upon the viscosity of carbon dioxide have been done: P. Phillips[3] measured by the transpiration method under the condition of the temperatures 20 ~ 40°C and the pressures 1 ~ 120 atm, H. Stakelbeck[2] determined by the falling-ball method at −15 ~ +40°C and up to 100 atm, E. Schröer and G. Becker[4] by the rolling-ball method at 20°C and 1 ~ 101 atm, S. N. Naldrett and O. Maass[5] investigated the viscosity of carbon dioxide in the critical region by the oscillating-disc method, and recently E. W. Comings, R. S. Egly[6] and E. W. Comings, B. J. Mayland, R. S. Egly[7] made measurements by the transpiration method up to 105°C and 171 atm. But their data failed to cover the wide range of temperature. In this paper the effect of pressure upon the viscosity of carbon dioxide is investigated at high temperatures.

On the effect of pressure upon the viscosity of ammonia, there has been only one report by H. Stakelbeck[2], who determined the effect by the falling-ball method at −20 ~ +80°C and 1 ~ 22 atm. Therefore, the authors measure the viscosity of ammonia in the wide range of temperature and pressure.

On the viscosity of acetylene, there have been only two reports at the ordinary pressure: one by T. Titani[8] at the temperatures between 20 and 120°C, and the other by R. Wobser and Fr. Müller[9] at 20 ~ 98°C. The effect of pressure upon the viscosity of acetylene is not known at all. Therefore, the temperature range at the ordinary pressure is expanded up to 250°C and the measurements are done at the temperatures 20 ~ 250°C and the pressures up to 100 kg/cm².

---

* Kyoto Technical University

[1] R. Kiyama and T. Makita, *This Journal*, **21**, 64 (1951)

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

[3] P. Phillips, *Proc. Roy. Soc., London*, A **87**, 48 (1912)

[4] E. Schröer and G. Becker, *Z. Phys. Chem.*, A **173**, 178 (1935)

[5] S. N. Naldrett and O. Maass, *Can. J. Research*, **18** B, 322 (1940)

[6] E. W. Comings and R. S. Egly, *Ind. Eng. Chem.*, **33**, 1224 (1941)

[7] E. W. Comings, B. J. Mayland and R. S. Egly, *C. A.*, **39**, 2439 (1945)

[8] T. Titani, *Bull. Chem. Soc. Japan*, **5**, 98 (1930)

[9] R. Wobser and Fr. Müller, *Kolloid Beihefte*, **52**, 265 (1941)

As there has been no report on the viscosity of argon and oxygen under high pressures, the present measurements are made in order to know the effects of the pressure and temperature upon the viscosity of argon and oxygen.

## Improvements of Apparatus

The viscometer previously described¹⁾ has been partly improved. For the viscometer-tube, soda-glass is replaced by Terex-glass after adequate heat treatment; when it is used at the pressures higher than 60kg/cm². In the cases of the measurement of carbon dioxide, ammonia and acetylene, the pipe connection of the mercury-trap with the viscometer-tube is electrically heated above their critical temperatures, and therefore the "metal-packing" 10) is used in the connection of the steel cylinder with the viscometer-tube. Furthermore, a stopper is set at the open end of the viscometer-tube for the purpose of avoiding the interchange of the high temperature gas in the viscometer-tube with the low temperature gas in the accessary parts.

## Sample Gases

The carbon dioxide and ammonia used in the present measurements are obtained by the redistillation from their liquids and the purity of the gases is more than 99.8% and 99.9%, respectively.

The purity of the acetylene used is 99.5～99.7%, the oxygen contained being less than 0.1% and the rest of the impurity nitrogen.

The commercial argon gas used consists of 97.8% of argon, 2.2% of nitrogen and oxygen less than 0.01%.

The purity of the oxygen used is 99.8%, the impurity contained being nitrogen.

The density and the viscosity of all the gases are calculated, assuming that they are pure. Even in the case of argon, the error of the viscosity for containing 2.2% of nitrogen is less than 1%.

## The Values of the Density

The values of the density of gases which is necessary for the calculation of the viscosity are obtained from the following compressibility data:

carbon dioxide; *A. Michels and C. Michels*11), *and E. H. Amagat*12),
ammonia; *C. H. Meyers and R. S. Jussup*13), *and J. A. Beattie and C. K. Lawrence*14),
acetylene; *R. Kiyama, T. Ikegami and K. Inoue*15),
argon; *L. Holborn and J. Otto*16),
oxygen; *I. Masson and G. F. Dolley*17), *and L. Holborn and J. Otto*16),

---

10) R. Kiyama, *This Journal*, 19, 21 (1945)
11) A. Michels and C. Michels, *Proc. Roy. Soc., London*, A 153, 201, 215 (1936)
12) Landolt-Börnstein, "*Physikalisch-chemische Tabellen*," Erster Bd., 113 (1923)
13) Landolt-Börnstein, *ibid.*, Dritter Erg. Bd., 100 (1935)
14) J. A. Beattie and C. K. Lawrence, *J. Am. Chem. Soc.*, 52, 6 (1930)
15) R. Kiyama, T. Ikegami and K. Inoue, *This Journal*, 21, 58 (1951)
16) L. Holborn and J. Otto, *Z. Phys.*, 23, 77 (1924): 30, 320 (1924): 33, 1 (1925)
17) I. Masson and G. F. Dolley, *Proc. Roy. Soc., London*, A 103, 524 (1923)

## Results and Considerations

**Carbon dioxide** The viscosity coefficients of carbon dioxide are shown in Table 1, and the values are plotted as the isotherms on the viscosity-pressure diagram in Fig. 1, in which the isotherms of 40°C obtained by P. Phillips3), H. Stakelbeck2), and E. W. Comings and R. S. Egly6), and the isotherm of 38°C by S. N. Naldrett and O. Maass5) are illustrated by the dotted curves to be compared with the authors' results. It is found that the isotherm of 50°C in the present measurement resembles reasonably the results at 40°C of both Stakelbeck and Comings and Egly, but that Phillips' values are considerably small at the pressures between 50 and and 85 kg/cm². Also the data at 38°C of Naldrett and Maass calculated from their viscosity-temperature isochores, are parallel to those of Phillips and cross over both Stakelbeck's and Comings' isotherms near 85 kg/cm². It has been known that the viscosity at low temperatures increases

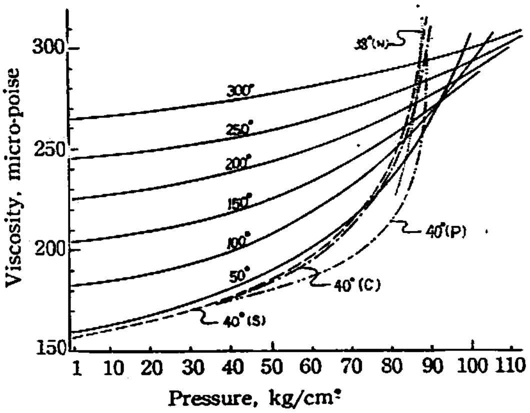

Fig. 1 Viscosity versus pressure diagram of $CO_2$
The values below 60 kg/cm² in this diagram were reported in the previous paper1). This diagram contains the values determined by the following investigators: 40°(P) shows the values of P. Phillips, 40°(S) of H. Stakelbeck, 40°(C) of E. W. Comings and R. S. Egly and 38°(N) of S. N. Naldrett and O. Maass.

Table 1
The viscosity of carbon dioxide

| 50°C | | | | 100°C | | | | 150°C | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| P | $\rho$ | $\eta$ | $\eta/\eta_1$ | P | $\rho$ | $\eta$ | $\eta/\eta_1$ | P | $\rho$ | $\eta$ | $\eta/\eta_1$ |
| 1.03 | 1.67 | 160 | 1.00 | 1.03 | 1.44 | 183 | 1.00 | 1.03 | 1.27 | 205 | 1.00 |
| 11.0 | 18.2 | 163 | 1.02 | 11.1 | 15.8 | 185 | 1.01 | 11.3 | 13.9 | 207 | 1.01 |
| 21.9 | 38.4 | 168 | 1.05 | 18.0 | 26.1 | 187 | 1.02 | 21.4 | 26.9 | 209 | 1.02 |
| 31.0 | 56.9 | 174 | 1.09 | 22.3 | 32.8 | 188 | 1.03 | 31.7 | 40.8 | 211 | 1.03 |
| 42.7 | 84.1 | 182 | 1.14 | 27.6 | 41.0 | 191 | 1.04 | 41.8 | 54.9 | 217 | 1.06 |
| 54.8 | 115.6 | 195 | 1.22 | 40.7 | 62.8 | 197 | 1.08 | 56.6 | 75.6 | 232 | 1.13 |
| 70.0 | 166.2 | 216 | 1.35 | 43.3 | 67.4 | 200 | 1.09 | 69.1 | 94.2 | 245 | 1.20 |
| 85.1 | 240.2 | 248 | 1.55 | 56.8 | 91.1 | 214 | 1.17 | 85.2 | 119.0 | 266 | 1.30 |
| 98.7 | 350.0 | 295 | 1.84 | 70.2 | 117.6 | 233 | 1.27 | 97.7 | 138.6 | 280 | 1.37 |
| | | | | 84.1 | 147.3 | 258 | 1.41 | | | | |
| | | | | 98.7 | 180.4 | 287 | 1.57 | | | | |

The Review of Physical Chemistry of Japan Vol. 22 No. 2 (1952)

| 200°C | | | | 250°C | | | | 300°C | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| P | $\rho$ | $\eta$ | $\eta/\eta_1$ | P | $\rho$ | $\eta$ | $\eta/\eta_1$ | P | $\rho$ | $\eta$ | $\eta/\eta_1$ |
| 1.03 | 1.14 | 225 | 1.00 | 1.03 | 1.03 | 245 | 1.00 | 1.03 | 0.942 | 264 | 1.00 |
| 11.3 | 12.8 | 229 | 1.02 | 10.6 | 10.8 | 247 | 1.01 | 12.4 | 11.5 | 266 | 1.01 |
| 21.5 | 24.3 | 232 | 1.03 | 20.7 | 21.2 | 250 | 1.02 | 22.4 | 20.7 | 269 | 1.02 |
| 32.0 | 36.4 | 234 | 1.04 | 32.5 | 33.1 | 254 | 1.04 | 31.4 | 29.0 | 271 | 1.03 |
| 41.3 | 47.3 | 239 | 1.06 | 42.6 | 43.7 | 257 | 1.05 | 42.7 | 39.6 | 275 | 1.04 |
| 41.7 | 47.8 | 238 | 1.06 | 60.6 | 62.3 | 264 | 1.08 | 59.3 | 55.2 | 281 | 1.06 |
| 57.3 | 66.5 | 248 | 1.10 | 70.3 | 73.5 | 271 | 1.11 | 70.7 | 66.1 | 285 | 1.08 |
| 69.0 | 80.9 | 257 | 1.14 | 83.7 | 87.6 | 280 | 1.14 | 84.1 | 78.9 | 291 | 1.10 |
| 83.7 | 98.9 | 271 | 1.20 | 97.4 | 102.6 | 292 | 1.19 | 97.0 | 91.4 | 298 | 1.13 |
| 98.7 | 118.1 | 288 | 1.28 | | | | | | | | |

P : Pressure, absolute kg/cm².
$\rho$ : Density, g/L.
$\eta$ : Viscosity-coefficient, micro-poise.
$\eta/\eta_1$ : The ratio of the viscosity at high pressure against the viscosity under ordinary pressure.

at rapid rate with pressure, and that the lower the temperature is, the more rapidly increases the viscosity. The isotherms of 40°C near the critical temperature (31.04°C), rise up near the critical pressure (75.23 kg/cm²) more rapidly than the isotherm of 50°C. The isotherms above 150°C do not cross each other up to 100 kg/cm².

It appears that the temperature coefficient of viscosity $\left(\frac{\partial \eta}{\partial T}\right)_p$[18] becomes smaller with increasing pressure and its sign is converted from positive to negative as shown by the crossing points in Fig. 1.

Fig. 2 shows the plots of viscosity versus density of carbon dioxide. The isotherms of 40° and 50°C near the critical temperature are the straight lines on the whole and the isotherms above 100°C are concave upwards. It is shown, refering to Table 1, that the effect of pressure upon the viscosity is stronger than that upon the density at temperatures far higher than the critical point.

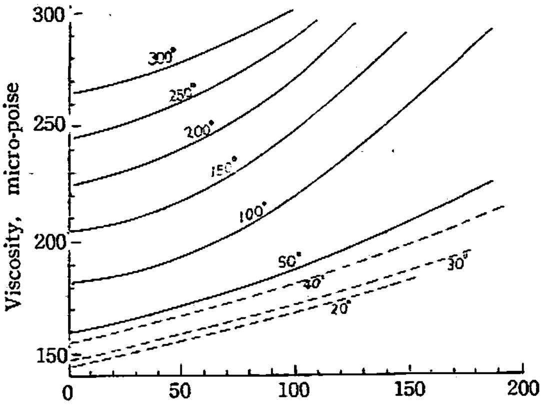

Fig. 2 Viscosity versus density diagram of $CO_2$ The Stakelbeck's values are shown in the dotted lines.

**Ammonia** The results obtained are shown in Table 2 and Fig. 3, the values determined by Stakelbeck[2] being plotted by the dotted lines in Fig. 3. The 45°C isotherm of Stakelbeck has a good resemblance to the present authors' values of 50°C, but

---

[18] R. H. Ewell, *J. Chem. Phys.*, 5, 571 (1937)

his values at 80°C become large too rapidly near 14atm and seem to be unreasonable in comparison with his own values at 45°C. From the authors' results, the isotherm of 80°C should cross that of 100°C near 40kg/cm².

Table 2

The viscosity of ammonia

| 50°C | | | | 100°C | | | | 150°C | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| P | $\rho$ | $\eta$ | $\eta/\eta_1$ | P | $\rho$ | $\eta$ | $\eta/\eta_1$ | P | $\rho$ | $\eta$ | $\eta/\eta_1$ |
| 1.03 | 0.652 | 108 | 1.00 | 1.03 | 0.565 | 126 | 1.00 | 1.03 | 0.498 | 144 | 1.00 |
| 6.5 | 4.25 | 121 | 1.12 | 10.1 | 5.70 | 134 | 1.06 | 10.7 | 6.09 | 148 | 1.03 |
| 8.8 | 5.83 | 125 | 1.16 | 10.4 | 5.90 | 133 | 1.06 | 22.1 | 11.2 | 155 | 1.08 |
| 11.3 | 7.60 | 128 | 1.19 | 20.4 | 12.1 | 142 | 1.13 | 38.4 | 20.5 | 166 | 1.15 |
| 16.7 | 12.1 | 142 | 1.31 | 25.4 | 15.6 | 150 | 1.19 | 50.1 | 28.0 | 176 | 1.22 |
| | | | | 29.6 | 18.6 | 151 | 1.20 | 68.4 | 41.2 | 193 | 1.34 |
| | | | | 40.1 | 27.1 | 160 | 1.27 | 81.7 | 52.7 | 205 | 1.42 |
| | | | | 46.2 | 32.8 | 170 | 1.35 | | | | |
| | | | | 53.3 | 40.6 | 181 | 1.44 | | | | |

| 200°C | | | | 250°C | | | | 300°C | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| P | $\rho$ | $\eta$ | $\eta/\eta_1$ | P | $\rho$ | $\eta$ | $\eta/\eta_1$ | P | $\rho$ | $\eta$ | $\eta/\eta_1$ |
| 1.03 | 0.445 | 163 | 1.00 | 1.03 | 0.403 | 179 | 1.00 | 1.03 | 0.368 | 198 | 1.00 |
| 11.0 | 4.76 | 167 | 1.02 | 11.7 | 4.55 | 182 | 1.02 | 13.7 | 4.84 | 200 | 1.01 |
| 21.2 | 9.33 | 172 | 1.06 | 18.0 | 7.02 | 183 | 1.02 | 26.1 | 9.40 | 201 | 1.02 |
| 40.4 | 18.6 | 182 | 1.12 | 37.8 | 15.25 | 191 | 1.07 | 38.4 | 13.85 | 204 | 1.03 |
| 54.6 | 25.8 | 191 | 1.17 | 41.0 | 16.6 | 195 | 1.09 | 60.0 | 22.1 | 214 | 1.08 |
| 69.7 | 34.2 | 201 | 1.23 | 54.6 | 22.4 | 200 | 1.12 | 63.2 | 23.4 | 215 | 1.09 |
| 80.5 | 40.5 | 209 | 1.28 | 68.1 | 28.5 | 207 | 1.16 | 68.4 | 25.5 | 218 | 1.10 |
| 97.0 | 50.8 | 229 | 1.40 | 84.4 | 36.2 | 220 | 1.23 | 84.1 | 31.7 | 226 | 1.14 |
| | | | | 97.0 | 42.5 | 230 | 1.29 | 92.6 | 35.3 | 232 | 1.17 |

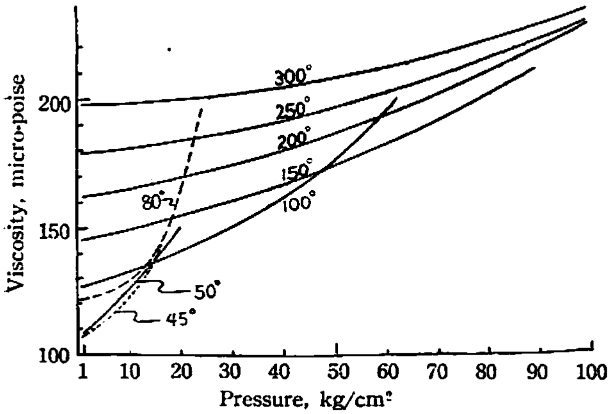

Fig. 3 Viscosity versus pressure diagram of ammonia
The Stakelbeck's values of 45° and 80°C are shown in the dotted lines.

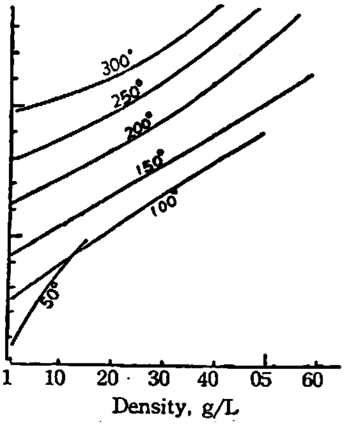

Fig. 4 Viscosity versus density diagram of ammonia

It is found that the temperature coefficient of viscosity at constant pressure, $\left(\frac{\partial\eta}{\partial T}\right)_p$, becomes smaller with increasing pressure in the same tendency as in the case of carbon dioxide. Above the critical temperature (132.4°C), the change of the sign of $\left(\frac{\partial\eta}{\partial T}\right)_p$ will take place at pressures moderately higher than 100 kg/cm², but it cannot be observed in this investigation.

The isotherms of viscosity versus density are plotted in Fig. 4. It shows that the isotherms of both 100°C and 150°C near the critical temperature are straight and the isotherms above 200°C are concave upwards, while the isotherm of 50°C is convex upwards. From these results, it is known that the effect of pressure upon the viscosity are linearly proportional to the increase of the density near the critical temperature, and then at the temperatures higher than the critical, the effect of pressure upon the viscosity are larger than that of pressure upon the density, and at the temperatures below the critical, the pressure has more influence on the density than on the viscosity.

**Acetylene** The viscosity coefficients of acetylene determined at the ordinary pressure are shown in Table 3, in which the values of Titani[8] and those of Wobser and Müller[9] are tabulated. The authors' values at the temperatures below 120°C are 1 ~ 2% larger than the values of Titani and of Wobser and Müller, and the values above 150°C can not be compared with any data.

Table 3
The viscosity of acetylene at the ordinary pressure

| Temperature °C | Viscosity coefficient, micro-poise Authors | T. Titani[8] | Wobser and Müller[9] |
|---|---|---|---|
| 20 | 103.0 | 102.0 | 99.8 |
| 40 | 109.3 | 107.9 | 106.7 |
| 60 | 115.3 | 113.1 | 113.2 |
| 80 | 121.4 | 119.8 | 120.1 |
| 100 | 127.7 | 125.4 | 126.9 |
| 120 | 133.0 | 131.8 | |
| 150 | 141.7 | | |
| 200 | 155.3 | | |
| 250 | 172.0 | | |

The results obtained under high pressures are shown in Table 4, and the viscosity-pressure isotherms plotted in Fig. 5. The values marked with stars in Table 4 are abnormally large as shown by the dotted lines in Fig. 5. This abnormality results from the deposition of a polymer of acetylene on the wall of the viscometer-tube, that is, the rolling velocity of the viscometer-ball is affected by the deposited polymer. R. Kiyama and H. Kinoshita[19] have researched the non-catalytic polymerization of acetylene at high temperatures and pressures, and found that the polymerization of

---

19) R. Kiyama and H. Kinoshita, *Unpublished.*

The Review of Physical Chemistry of Japan Vol. 22 No. 2 (1952)

Table 4

The viscosity of acetylene under high pressure

| 20°C | | | | 60°C | | | | 100°C | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| P | $\rho$ | $\eta$ | $\eta/\eta_1$ | P | $\rho$ | $\eta$ | $\eta/\eta_1$ | P | $\rho$ | $\eta$ | $\eta/\eta_1$ |
| 1.03 | 1.0886 | 103 | 1.00 | 1.03 | 0.9613 | 115 | 1.00 | 1.03 | 0.8581 | 128 | 1.00 |
| 11.3 | 12.85 | 106 | 1.03 | 13.7 | 13.05 | 121 | 1.05 | 14.2 | 12.15 | 130 | 1.02 |
| 19.7 | 24.10 | 114 | 1.11 | 27.1 | 28.40 | 129 | 1.12 | 28.4 | 25.65 | 138 | 1.08 |
| 27.7 | 37.20 | 121 | 1.17 | 41.7 | 49.20 | 138 | 1.20 | 41.0 | 39.25 | 144 | 1.13 |
| 36.2 | 53.70 | 135 | 1.31 | 55.2 | 74.55 | 148 | 1.29 | 55.8 | 57.20 | 153 | 1.20 |
| | | | | 67.7 | 107.15 | 164 | 1.43 | 68.7 | 74.70 | 162 | 1.27 |
| | | | | 83.4 | 170.35 | 198 | 1.72 | 85.9 | 101.30 | 180 | 1.41 |
| | | | | | | | | 96.7 | 120.70 | 199 | 1.55 |

| 150°C | | | | 200°C | | | | 250°C | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| P | $\rho$ | $\eta$ | $\eta/\eta_1$ | P | $\rho$ | $\eta$ | $\eta/\eta_1$ | P | $\rho$ | $\eta$ | $\eta/\eta_1$ |
| 1.03 | 0.7565 | 142 | 1.00 | 1.03 | 0.6765 | 155 | 1.00 | 1.03 | 0.6117 | 172 | 1.00 |
| 12.7 | 9.45 | 145 | 1.02 | 13.3 | 8.70 | 157 | 1.01 | 12.7 | 7.58 | 175 | 1.02 |
| 29.3 | 22.50 | 151 | 1.06 | 26.9 | 18.10 | 163 | 1.05 | 27.4 | 16.50 | 179 | 1.04 |
| 41.8 | 33.40 | 156 | 1.10 | 42.8 | 29.93 | 170 | 1.10 | 43.5 | 27.25 | 193 | 1.12* |
| 57.1 | 47.90 | 163 | 1.14 | 56.8 | 41.35 | 177 | 1.14 | 53.9 | 34.20 | 269 | 1.56* |
| 71.4 | 61.85 | 171 | 1.20 | 70.0 | 51.95 | 185 | 1.19 | 67.1 | 43.20 | 262 | 1.52* |
| 85.8 | 76.75 | 186 | 1.31 | 85.2 | 64.10 | 194 | 1.25 | 83.4 | 54.65 | 262 | 1.52* |
| 97.0 | 89.00 | 203 | 1.43 | 98.1 | 74.50 | 250 | 1.61* | 97.0 | 64.25 | 266 | 1.55* |

acetylene began near 250°C on the surface of a steel vessel, and that 10% of acetylene at 250°C and 31 atm polymerized in 33 hours and 3% at 250°C and 10 atm in 31 hours. In the case of the authors' measurements of viscosity, the viscometer-tube is kept for two hours at a given temperature and pressure. A slight brownish-yellow colour of polymer is recognized on the wall of the viscometer-tube at 200°C and 98.1 kg/cm². At 250°C, no colour is observed at all under the pressures below 43.5 kg/cm², but the deposition

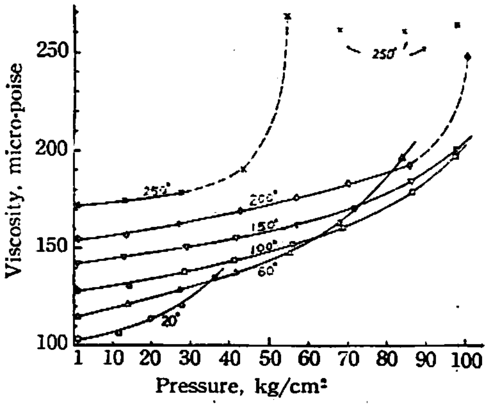

Fig. 5 Viscosity versus pressure diagram of acetylene

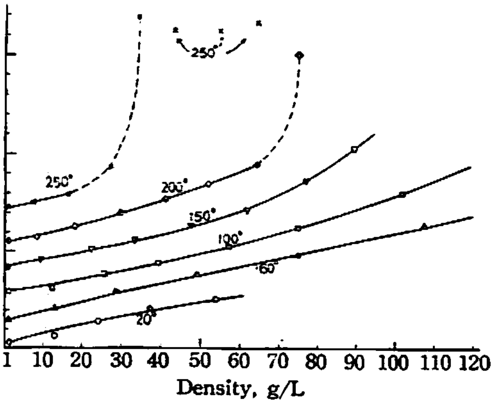

Fig. 6 Viscosity versus density diagram of acetylene

of polymer rapidly increases under the pressures above 53.9 kg/cm$^2$ and any deposit of solid or liquid on the wall of the viscometer-tube makes the measurement of viscosity impossible.

The viscosity-pressure isotherms in Fig. 5 have a resemblance to the cases of both carbon dioxide and ammonia. It is found that the viscosity at low temperatures increases with increasing pressure at more rapid rate than that at high temperatures. Therefore, the sign of the temperature coefficient of viscosity at constant pressure, $\left(\frac{\partial\eta}{\partial T}\right)_p$, is converted from positive to negative. As the sign of $\left(\frac{\partial\eta}{\partial T}\right)_p$ of the liquids is negative[18], it seems that the high-pressure gas shows the property like liquid in regard to the sign of $\left(\frac{\partial\eta}{\partial T}\right)_p$.

Fig. 6 is the plots of viscosity versus density of acetylene. The isotherms of 20 and 60°C near critical temperature (38.5°C) are the straight lines on the whole and the isotherms above 100°C are concave upwards, just as discussed in the cases of both carbon dioxide and ammonia.

**Argon** The viscosity of argon is tabulated in Table 5, the viscosity-pressure isotherms being shown in Fig. 7, and the viscosity-density isotherms in Fig. 8. There is no change of the sign of the temperature coefficient of viscosity at constant pressure, $\left(\frac{\partial\eta}{\partial T}\right)_p$, observed in the cases of carbon dioxide and ammonia, because the measuring temperatures are far higher than the critical temperature (−122.44°C). But the value of

Table 5
The viscosity of argon

| 50°C | | | | 100°C | | | | 150°C | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $P$ | $\rho$ | $\eta$ | $\eta/\eta_1$ | $P$ | $\rho$ | $\eta$ | $\eta/\eta_1$ | $P$ | $\rho$ | $\eta$ | $\eta/\eta_1$ |
| 1.03 | 1.507 | 241 | 1.00 | 1.03 | 1.305 | 271 | 1.00 | 1.03 | 1.150 | 295 | 1.00 |
| 11.5 | 16.90 | 244 | 1.01 | 12.7 | 16.15 | 273 | 1.01 | 14.2 | 15.90 | 296 | 1.003 |
| 24.4 | 36.00 | 249 | 1.03 | 24.4 | 30.95 | 275 | 1.02 | 26.3 | 29.30 | 298 | 1.01 |
| 41.0 | 60.70 | 253 | 1.05 | 39.4 | 49.60 | 278 | 1.03 | 42.0 | 46.70 | 304 | 1.03 |
| 55.8 | 82.80 | 258 | 1.07 | 51.7 | 65.55 | 283 | 1.04 | 55.8 | 61.95 | 308 | 1.04 |
| 67.9 | 101.10 | 265 | 1.10 | 68.7 | 87.15 | 290 | 1.07 | 69.0 | 76.40 | 313 | 1.06 |
| 82.4 | 123.10 | 270 | 1.12 | 82.5 | 104.60 | 297 | 1.10 | 81.9 | 90.60 | 320 | 1.08 |
| 97.0 | 145.15 | 283 | 1.17 | 98.2 | 124.40 | 305 | 1.13 | 97.0 | 106.90 | 326 | 1.11 |

| 200°C | | | | 300°C | | | |
|---|---|---|---|---|---|---|---|
| $P$ | $\rho$ | $\eta$ | $\eta/\eta_1$ | $P$ | $\rho$ | $\eta$ | $\eta/\eta_1$ |
| 1.03 | 1.029 | 320 | 1.00 | 1.03 | 0.849 | 362 | 1.00 |
| 13.0 | 13.00 | 322 | 1.01 | 14.2 | 11.65 | 363 | 1.003 |
| 26.7 | 26.50 | 326 | 1.02 | 25.9 | 21.25 | 367 | 1.01 |
| 44.9 | 44.50 | 331 | 1.03 | 42.7 | 34.75 | 369 | 1.02 |
| 55.4 | 54.75 | 333 | 1.04 | 56.2 | 45.65 | 373 | 1.03 |
| 67.8 | 66.90 | 340 | 1.06 | 67.4 | 54.60 | 378 | 1.04 |
| 81.0 | 79.60 | 346 | 1.08 | 81.4 | 65.60 | 384 | 1.06 |
| 98.4 | 96.15 | 351 | 1.10 | 97.9 | 78.55 | 389 | 1.07 |

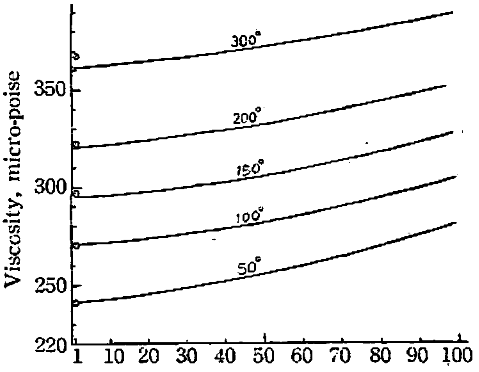

Fig. 7 Viscosity versus pressure diagram of argon

The points plotted by ⊙ are the values at the ordinary pressure by M. Trautz et al[20, 21].

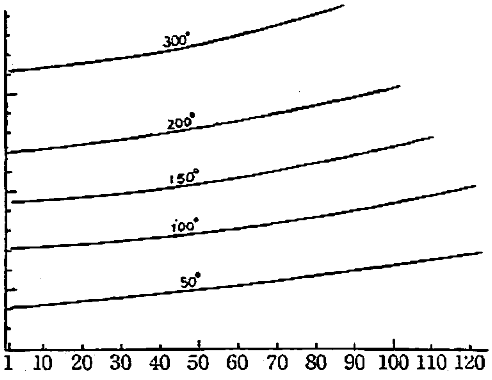

Fig. 8 Viscosity versus density diagram of argon

$\left(\frac{\partial\eta}{\partial T}\right)_p$ decreases slowly with increasing pressure.

As the values of the viscosity at the elevated pressure have not been reported, no comparision with the authors' results can be done. The values at the ordinary pressure, therefore, are compared with the data of M. Trautz and H. E. Binkele[20], and of M. Trautz and R. Zink[21], which are the most credible values over the wide range of temperature and are plotted in Fig. 7. It is found that the values obtained below 200°C in the present measurements coincide with Trautz's values within less than 0.5% error, and that the value of 300°C is 1.5% lower.

**Oxygen** The viscosity of oxygen obtained is shown in Table 6, the viscosity-pressure isotherms being plotted in Fig. 9 and the viscosity-density isotherms in Fig. 10. Just as mentioned on argon, it is found that the viscosity at low temperatures

Table 6

The viscosity of oxygen

| 25°C | | | | 50°C | | | | 100°C | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| P | $\rho$ | $\eta$ | $\eta/\eta_1$ | P | $\rho$ | $\eta$ | $\eta/\eta_1$ | P | $\rho$ | $\eta$ | $\eta/\eta_1$ |
| 1.03 | 1.309 | 206 | 1.00 | 1.03 | 1.208 | 220 | 1.00 | 1.03 | 1.046 | 245 | 1.00 |
| 18.0 | 23.22 | 215 | 1.04 | 18.2 | 21.40 | 226 | 1.03 | 18.2 | 18.40 | 251 | 1.02 |
| 33.1 | 42.72 | 221 | 1.07 | 34.0 | 40.20 | 233 | 1.06 | 35.3 | 35.72 | 256 | 1.04 |
| 49.8 | 65.00 | 232 | 1.13 | 49.8 | 59.10 | 241 | 1.10 | 50.8 | 51.50 | 261 | 1.06 |
| 64.2 | 84.30 | 240 | 1.16 | 65.5 | 78.05 | 250 | 1.14 | 68.5 | 69.50 | 270 | 1.10 |
| 78.7 | 104.0 | 249 | 1.21 | 79.0 | 94.60 | 259 | 1.18 | 79.9 | 81.05 | 278 | 1.13 |
| 92.9 | 123.3 | 258 | 1.25 | 97.4 | 116.95 | 268 | 1.22 | 98.4 | 99.85 | 285 | 1.16 |

---

20) M. Trautz and H. E. Binkele, *Ann. Physik*, (5) **5**, 561 (1930)

21) M. Trautz and R. Zink, *ibid.*, **7**, 427 (1930)

| 150°C | | | | 200°C | | | |
|---|---|---|---|---|---|---|---|
| P | $\rho$ | $\eta$ | $\eta/\eta_1$ | P | $\rho$ | $\eta$ | $\eta/\eta_1$ |
| 1.03 | 0.922 | 268 | 1.00 | 1.03 | 0.825 | 290 | 1.00 |
| 18.1 | 15.60 | 273 | 1.02 | 18.5 | 14.05 | 293 | 1.01 |
| 35.6 | 30.92 | 276 | 1.03 | 34.3 | 26.10 | 295 | 1.02 |
| 48.2 | 42.25 | 279 | 1.04 | 50.4 | 38.95 | 300 | 1.03 |
| 62.9 | 55.50 | 283 | 1.05 | 64.7 | 50.10 | 304 | 1.05 |
| 78.4 | 69.30 | 289 | 1.08 | 81.0 | 62.70 | 310 | 1.07 |
| 96.3 | 84.70 | 299 | 1.11 | 99.5 | 76.60 | 316 | 1.09 |

increases at more rapid rate with increasing pressure than at high temperatures in Fig. 9, and that the isotherms in Fig. 10 are smooth and parallel each other, because the measuring temperatures are far higher than the critical temperature (−118.82°C).

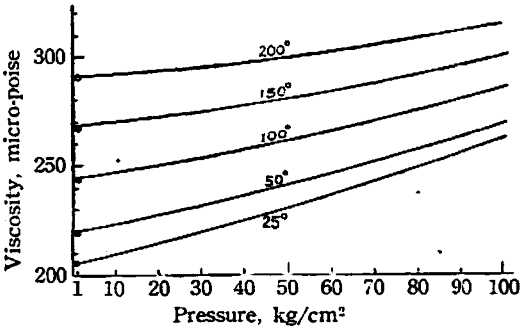

Fig. 9 Viscosity versus pressure diagram of oxygen

The points plotted by ⊙ are the values at the ordinary pressure by M. Trautz et al[22, 23].

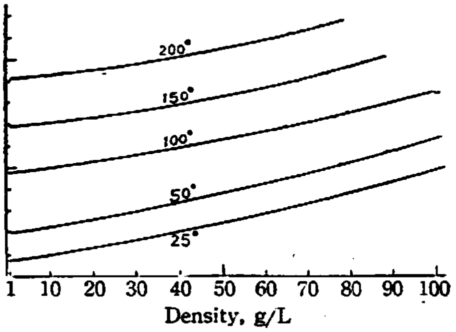

Fig. 10 Viscosity versus density diagram of oxygen

The values at the ordinary pressure are compared with the data obtained by M. Trautz and A. Melster[22] and by M. Trautz and K. G. Sorg[23], which are plotted in Fig. 9. The authors' results in all the temperature range show a good agreement within 0.5%.

The authors are indebted to the Department of Education for the Grant to the Cooperative Research (The Fundamental Research on High Pressure Industries).

*The Laboratory of Physical Chemistry,*
*Kyoto University*

---

22) M. Trautz and A. Melster, *Ann. Physik*, (5) 7, 409 (1930)

23) M. Trautz and K. G. Sorg, *ibid.*, 10, 81 (1931)