

## VISCOSITY OF ARGON AND OF ARGON-AMMONIA MIXTURES UNDER PRESSURES\*

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The viscosity of argon and of four argon-ammonia gaseous mixtures was measured using an oscillating disk viscometer at temperatures, 25, 50, 75, and 100°C; for argon, at the pressure range up to about  $120 \times 10^5$  Pa; and for argon-ammonia mixtures, up to around the saturated vapor pressure of ammonia at each temperature. The accuracy of the measurements was estimated to be within  $\pm 0.3\%$ .

The gas viscosity values of dilute binary mixtures were calculated by applying a correction factor, which was set up by use of critical compressibility factors. The calculated values were in better agreement with the experimental ones than those calculated by original Chapman-Enskog's method.

The initial density dependence of the viscosity,  $\eta_0^{-1} (\partial\eta/\partial\rho)_{\rho \rightarrow 0}$ , of argon-ammonia mixtures was obtained from the experimental values, and the effects of the concentration of nonpolar gases and of temperature on the initial density dependence were compared with those in the case of the nitrogen-ammonia system and of the hydrogen-ammonia system, where  $\eta$  is viscosity of gas,  $\rho$  density, and  $\eta_0$  the viscosity extrapolated to zero density. It was concluded from the comparison that molecular association of polar gases was hindered by the presence of nonpolar molecules and by a rise in temperature, and that the larger the molecular weight of a nonpolar gas was, the more strongly the nonpolar molecules hindered molecular association of polar substances.

By taking into account the mole fraction of nonpolar gases, the initial density dependence of the viscosity could be correlated with the temperature reduced by the critical temperature of the mixtures, and a similar tendency was observed regardless of the system.

### Introduction

This study is one of the researches to measure the gas viscosity of nonpolar-polar mixtures containing ammonia as a polar gas under pressures. The viscosities of the nitrogen-ammonia system<sup>1)</sup> and of the hydrogen-ammonia system<sup>2)</sup> were already determined, and the viscosities of argon and of argon-ammonia mixtures are presented in this paper. In order to investigate the effect of the molecular weight of a nonpolar gas on the viscosity of a polar gas, argon was used because its molecular weight is larger than that of nitrogen. The viscosity of the argon-ammonia system under pressures was measured by Iwasaki *et al.*<sup>3)</sup> using an oscillating disk viscometer, but only at 20 and 30°C. The viscosity at atmospheric pressure was measured by Chakraborti *et al.*<sup>4)</sup> (25 to 80°C) using a capillary-

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1) M. Hongo and H. Iwasaki, *This Journal*, **47**, 90 (1977)

2) M. Hongo and H. Iwasaki, *ibid.*, **48**, 1 (1978)

3) H. Iwasaki, J. Kestin, and A. Nagashima, *J. Chem. Phys.*, **40**, 2988 (1964)

4) P.K. Chakraborti and P. Gray, *Trans. Faraday Soc.*, **61**, 2422 (1965)

flow viscometer and by Rakshit *et al.*<sup>5)</sup> (−35 to 35°C) by the use of an oscillating disk viscometer.

In this study, the measurements of the viscosity of argon-ammonia mixtures were performed on a precision oscillating disk viscometer, which was the same as that previously used<sup>1,2)</sup>, at temperatures of 25, 50, 75, and 100°C, and over the range of pressure up to about  $120 \times 10^5$  Pa for argon and up to around the saturated vapor pressure of ammonia at each temperature for argon-ammonia mixtures. The mole fractions of argon in the mixtures were approximately 0.2, 0.4, 0.6, and 0.8.

### Experimental Method and Calculation of Viscosity

The gas viscosity was evaluated by the same method as that used by Iwasaki *et al.*<sup>6)</sup> The empirical value  $C_N'$  of the apparatus constant,  $C_N$ , required for the evaluation of the viscosity was determined by the calibration measurements which were made using nitrogen at temperature of 25°C and at pressures below  $25 \times 10^5$  Pa. The value of  $C_N'$  obtained from the calibration measurements was 1.1355 from 25 to 75°C, and 1.1378 at 100°C.

The density of argon was obtained through the  $PV$ -values by Michels *et al.*<sup>7)</sup> and that of argon-ammonia mixtures was evaluated from the  $Vri$ -chart<sup>8)</sup> in the same way as that used in the previous papers<sup>1,2)</sup>, where  $Vri$  is the ideal reduced molar volume.

Argon was supplied from the Nippon Oxygen Co., Ltd. and its purity was above 99.994%. Ammonia was purified through distillation as described before<sup>1)</sup>.

The experimental accuracy was estimated to be within  $\pm 0.3\%$ .

### Results

The viscosity values obtained for argon are shown in Table 1 and plotted as a viscosity *vs.* density diagram in Fig. 1. The deviations of the measured viscosity values from the smoothed curves are all within  $\pm 0.2\%$ . The slopes of the viscosity isotherm,  $(\partial\eta/\partial\rho)_T$ , are always positive and almost the same in the experimental conditions, where  $\eta$  is viscosity of gas and  $\rho$  is density. The viscosity of argon under pressures, so far, was measured by Michels *et al.*<sup>9)</sup> from 0 to 75°C below  $2000 \times 10^5$  Pa; by Iwasaki *et al.*<sup>10)</sup> from 25 to 150°C up to  $130 \times 10^5$  Pa; by Flynn *et al.*<sup>11)</sup> from −78 to 100°C below  $200 \times 10^5$  Pa; by Reynes *et al.*<sup>12)</sup> from 100 to 200°C up to  $830 \times 10^5$  Pa; and by Gracki *et al.*<sup>13)</sup> from −100 to 25°C below  $170 \times 10^5$  Pa. These measurements were made using a capillary-flow viscometer, except

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- 7) A. Michels, Hub. Wijker and Hk. Wijker, *ibid.*, **15**, 627 (1949)
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- 13) J.A. Gracki, G.P. Flynn and J. Ross, *J. Chem. Phys.*, **51**, 3856 (1969)

## Viscosity of Argon and of Argon-Ammonia Mixtures under Pressures

Table 1 Viscosity of argon

| Pressure<br>$10^5$ Pa | Density<br>$10^3 \text{ kg} \cdot \text{m}^{-3}$ | Viscosity<br>$10^{-7} \text{ Pa} \cdot \text{s}$ | Pressure<br>$10^5$ Pa | Density<br>$10^3 \text{ kg} \cdot \text{m}^{-3}$ | Viscosity<br>$10^{-7} \text{ Pa} \cdot \text{s}$ |
|-----------------------|--|--|-----------------------|--|--|
| 25°C                  |  |  | 75°C                  |  |  |
| 1.23                  | 0.00197  | 226.1  | 1.26                  | 0.00173  | 256.5  |
| 1.47                  | 0.00236  | 226.6  | 1.26                  | 0.00173  | 256.6  |
| 2.52                  | 0.00405  | 226.7  | 2.03                  | 0.00278  | 256.4  |
| 5.06                  | 0.00812  | 226.8  | 5.17                  | 0.00710  | 257.0  |
| 5.12                  | 0.00822  | 226.9  | 10.11                 | 0.01388  | 257.5  |
| 10.15                 | 0.01632  | 228.1  | 20.37                 | 0.02815  | 259.7  |
| 10.19                 | 0.01637  | 227.9  | 41.38                 | 0.05350  | 264.1  |
| 20.39                 | 0.03323  | 229.9  | 61.11                 | 0.08525  | 268.5  |
| 23.64                 | 0.03919  | 231.0  | 82.43                 | 0.1152   | 274.5  |
| 41.17                 | 0.06797  | 235.4  | 102.81                | 0.14378  | 280.7  |
| 61.73                 | 0.1030   | 242.0  | 113.39                | 0.16667  | 286.4  |
| 83.18                 | 0.1398   | 249.7  |                       |  |  |
| 104.59                | 0.17696  | 258.6  | 100°C                 |  |  |
| 125.30                | 0.21291  | 267.9  | 1.23                  | 0.00159  | 272.8  |
| 125.35                | 0.21296  | 268.2  | 1.36                  | 0.00176  | 273.0  |
|                       |  |  | 2.03                  | 0.00262  | 273.5  |
| 50°C                  |  |  | 5.06                  | 0.00654  | 273.6  |
| 1.24                  | 0.00183  | 242.0  | 10.11                 | 0.01308  | 274.5  |
| 1.52                  | 0.00225  | 242.1  | 20.27                 | 0.02614  | 276.4  |
| 1.54                  | 0.00228  | 242.0  | 40.44                 | 0.05227  | 280.0  |
| 5.12                  | 0.00757  | 242.8  | 61.05                 | 0.07893  | 285.1  |
| 5.12                  | 0.00757  | 242.7  | 82.12                 | 0.1062   | 290.1  |
| 10.12                 | 0.01498  | 243.5  | 102.60                | 0.13244  | 295.9  |
| 10.19                 | 0.01508  | 243.5  | 122.01                | 0.15716  | 301.7  |
| 20.42                 | 0.03054  | 245.4  | 125.98                | 0.16219  | 302.8  |
| 41.16                 | 0.06212  | 250.0  |                       |  |  |
| 61.29                 | 0.09299  | 255.6  |                       |  |  |
| 81.58                 | 0.1240   | 261.7  |                       |  |  |
| 102.24                | 0.15639  | 270.1  |                       |  |  |
| 121.54                | 0.18595  | 276.8  |                       |  |  |
| 121.54                | 0.18595  | 277.5  |                       |  |  |

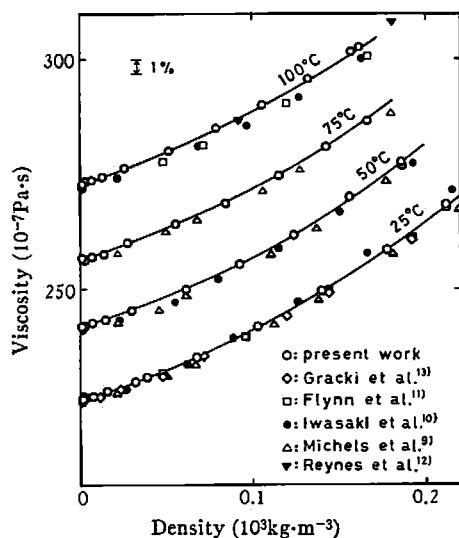


Fig. 1 Viscosity of argon

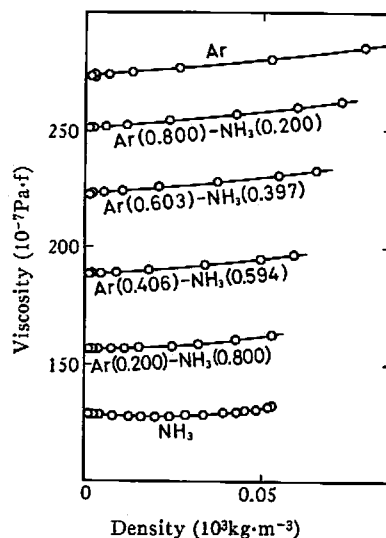


Fig. 2 Viscosity of argon-ammonia system at 100°C

that of Iwasaki *et al.*<sup>10)</sup> who used an oscillating disk viscometer. As shown in Fig. 1, the viscosity values obtained in this work are in agreement with those obtained in the investigations mentioned above within the experimental error.

The viscosity measurements for four argon-ammonia mixtures were carried out at the same temperatures as for argon and at pressures up to around the saturated vapor pressure of ammonia at each temperature, *i.e.*, about  $10 \times 10^5$  Pa at 25°C,  $20 \times 10^5$  Pa at 50°C,  $35 \times 10^5$  Pa at 75°C, and  $60 \times 10^5$  Pa at 100°C. The viscosity values obtained for the mixtures are given in Table 2. The results obtained for the gaseous mixtures at 100°C are shown in Fig. 2. The viscosity values of pure ammonia shown in Fig. 2 are those reported in Ref. 1. As shown in Fig. 2, the initial slope of the viscosity-density curves for the gaseous mixtures,  $(\partial\eta/\partial\rho)_{p \rightarrow 0}$ , increases as the mole fraction of argon increases, and becomes nearly constant above 0.406 mole fraction of argon.

Table 2 Viscosity of argon-ammonia mixtures

| Pressure<br>10 <sup>5</sup> Pa    | Density<br>10 <sup>3</sup> kg·m <sup>-3</sup> | Viscosity<br>10 <sup>-7</sup> Pa·s | Pressure<br>10 <sup>5</sup> Pa    | Density<br>10 <sup>3</sup> kg·m <sup>-3</sup> | Viscosity<br>10 <sup>-7</sup> Pa·s | Pressure<br>10 <sup>5</sup> Pa    | Density<br>10 <sup>3</sup> kg·m <sup>-3</sup> | Viscosity<br>10 <sup>-7</sup> Pa·s |
|-----------------------------------|---|------------------------------------|-----------------------------------|---|------------------------------------|-----------------------------------|---|------------------------------------|
| 25°C                              |   |                                    | 50°C                              |   |                                    | 75°C                              |   |                                    |
| Ar(0.208)-NH <sub>3</sub> (0.792) |   |                                    | Ar(0.600)-NH <sub>3</sub> (0.400) |   |                                    | Ar(0.794)-NH <sub>3</sub> (0.206) |   |                                    |
| 1.23                              | 0.00108                                       | 129.5                              | 1.24                              | 0.00142                                       | 196.4                              | 1.24                              | 0.00150                                       | 234.7                              |
| 1.33                              | 0.00117                                       | 129.5                              | 1.30                              | 0.00149                                       | 196.7                              | 2.03                              | 0.00247                                       | 234.7                              |
| 2.53                              | 0.00223                                       | 129.5                              | 2.02                              | 0.00231                                       | 196.5                              | 5.09                              | 0.00619                                       | 235.2                              |
| 4.54                              | 0.00399                                       | 129.2                              | 3.04                              | 0.00349                                       | 196.8                              | 10.11                             | 0.01231                                       | 236.1                              |
| 6.65                              | 0.00591                                       | 129.0                              | 5.12                              | 0.00590                                       | 197.2                              | 15.23                             | 0.01864                                       | 237.0                              |
| 8.67                              | 0.00787                                       | 128.0                              | 10.13                             | 0.01179                                       | 197.8                              | 25.30                             | 0.03136                                       | 238.9                              |
| 10.18                             | 0.009425                                      | 128.8                              | 15.26                             | 0.01803                                       | 198.5                              | 36.16                             | 0.04540                                       | 240.8                              |
| Ar(0.397)-NH <sub>3</sub> (0.603) |   |                                    | 20.25                             | 0.02440                                       | 199.6                              | 39.41                             | 0.04958                                       | 241.5                              |
| 1.23                              | 0.00129                                       | 157.5                              | 22.69                             | 0.02758                                       | 199.9                              | 100°C                             |   |                                    |
| 1.41                              | 0.00149                                       | 157.7                              | Ar(0.801)-NH <sub>3</sub> (0.199) |   |                                    | Ar(0.200)-NH <sub>3</sub> (0.800) |   |                                    |
| 3.06                              | 0.00323                                       | 157.8                              | 1.23                              | 0.00161                                       | 220.9                              | 1.18                              | 0.000819                                      | 156.3                              |
| 5.12                              | 0.00539                                       | 158.0                              | 1.26                              | 0.00165                                       | 221.0                              | 1.26                              | 0.000876                                      | 156.4                              |
| 7.10                              | 0.00763                                       | 158.1                              | 2.03                              | 0.00267                                       | 221.1                              | 1.44                              | 0.00100                                       | 156.5                              |
| 9.17                              | 0.0100  | 158.1                              | 3.05                              | 0.00400                                       | 221.2                              | 2.03                              | 0.00141                                       | 156.4                              |
| 10.68                             | 0.01183                                       | 158.4                              | 5.08                              | 0.00668                                       | 221.5                              | 3.00                              | 0.00209                                       | 156.5                              |
| Ar(0.602)-NH <sub>3</sub> (0.398) |   |                                    | 10.13                             | 0.01342                                       | 222.7                              | 5.07                              | 0.00353                                       | 156.4                              |
| 1.18                              | 0.00146                                       | 184.8                              | 15.18                             | 0.02024                                       | 223.3                              | 10.13                             | 0.007260                                      | 156.5                              |
| 1.28                              | 0.00159                                       | 185.0                              | 20.32                             | 0.02749                                       | 224.2                              | 15.15                             | 0.01112                                       | 156.7                              |
| 3.01                              | 0.00374                                       | 185.1                              | 24.15                             | 0.03285                                       | 225.0                              | 20.27                             | 0.01512                                       | 157.0                              |
| 5.16                              | 0.00641                                       | 185.7                              | 75°C                              |   |                                    | 31.76                             | 0.02441                                       | 157.6                              |
| 7.63                              | 0.00961                                       | 186.0                              | Ar(0.202)-NH <sub>3</sub> (0.798) |   |                                    | 40.43                             | 0.03193                                       | 158.7                              |
| 9.90                              | 0.0126  | 186.2                              | 1.20                              | 0.000895                                      | 148.0                              | 51.06                             | 0.04228                                       | 160.5                              |
| 11.42                             | 0.01467                                       | 186.4                              | 1.25                              | 0.000933                                      | 148.0                              | 60.56                             | 0.05269                                       | 162.5                              |
| Ar(0.800)-NH <sub>3</sub> (0.200) |   |                                    | 2.03                              | 0.00152                                       | 148.0                              | Ar(0.406)-NH <sub>3</sub> (0.594) |   |                                    |
| 1.25                              | 0.00178                                       | 208.4                              | 5.06                              | 0.00378                                       | 148.0                              | 1.24                              | 0.00105                                       | 188.2                              |
| 1.45                              | 0.00207                                       | 208.2                              | 10.14                             | 0.007830                                      | 148.1                              | 2.04                              | 0.00173                                       | 188.3                              |
| 2.99                              | 0.00426                                       | 208.5                              | 20.28                             | 0.01650                                       | 148.4                              | 5.05                              | 0.00428                                       | 188.6                              |
| 5.14                              | 0.00733                                       | 208.9                              | 30.82                             | 0.02642                                       | 149.1                              | 10.13                             | 0.008730                                      | 189.0                              |
| 7.15                              | 0.0103  | 209.2                              | 35.76                             | 0.03112                                       | 149.5                              | 20.29                             | 0.01788                                       | 190.1                              |
| 10.22                             | 0.01489                                       | 209.9                              | Ar(0.394)-NH <sub>3</sub> (0.606) |   |                                    | 36.62                             | 0.03362                                       | 192.2                              |
| 12.35                             | 0.01835                                       | 210.3                              | 1.18                              | 0.00106                                       | 177.6                              | 51.70                             | 0.04938                                       | 194.9                              |
| 50°C                              |   |                                    | 1.24                              | 0.00111                                       | 177.4                              | 60.80                             | 0.05907                                       | 196.8                              |
| Ar(0.211)-NH <sub>3</sub> (0.789) |   |                                    | 2.01                              | 0.00181                                       | 177.7                              | Ar(0.603)-NH <sub>3</sub> (0.397) |   |                                    |
| 1.17                              | 0.000949                                      | 140.2                              | 5.08                              | 0.00457                                       | 177.9                              | 1.22                              | 0.00121                                       | 222.0                              |
| 1.26                              | 0.00102                                       | 140.4                              | 10.14                             | 0.009363                                      | 178.3                              | 2.03                              | 0.00202                                       | 222.2                              |
| 2.03                              | 0.00165                                       | 140.2                              | 20.34                             | 0.01947                                       | 179.2                              | 5.05                              | 0.00502                                       | 223.0                              |
| 5.08                              | 0.00420                                       | 140.2                              | 31.15                             | 0.03080                                       | 180.6                              | 10.14                             | 0.01019                                       | 223.5                              |
| 10.17                             | 0.008782                                      | 140.2                              | 36.74                             | 0.03682                                       | 181.5                              | 20.29                             | 0.02064                                       | 225.2                              |
| 15.18                             | 0.01349                                       | 140.2                              | Ar(0.597)-NH <sub>3</sub> (0.403) |   |                                    | 36.11                             | 0.03771                                       | 227.5                              |
| 20.39                             | 0.01868                                       | 140.4                              | 1.22                              | 0.00129                                       | 208.2                              | 51.39                             | 0.05455                                       | 230.2                              |
| Ar(0.403)-NH <sub>3</sub> (0.597) |   |                                    | 1.37                              | 0.00145                                       | 208.3                              | 60.86                             | 0.06520                                       | 232.6                              |
| 1.23                              | 0.00120                                       | 168.3                              | 2.03                              | 0.00215                                       | 208.6                              | Ar(0.800)-NH <sub>3</sub> (0.200) |   |                                    |
| 1.42                              | 0.00139                                       | 168.3                              | 5.07                              | 0.00538                                       | 209.2                              | 1.24                              | 0.00141                                       | 250.3                              |
| 2.51                              | 0.00246                                       | 168.4                              | 10.13                             | 0.01089                                       | 209.8                              | 2.03                              | 0.00231                                       | 250.4                              |
| 5.09                              | 0.00499                                       | 168.7                              | 20.27                             | 0.02228                                       | 211.4                              | 5.06                              | 0.00576                                       | 251.0                              |
| 10.17                             | 0.01028                                       | 169.2                              | 30.92                             | 0.03482                                       | 213.2                              | 10.13                             | 0.01155                                       | 251.7                              |
| 15.14                             | 0.01566                                       | 169.5                              | 37.43                             | 0.04278                                       | 214.3                              | 20.30                             | 0.02342                                       | 253.9                              |
| 20.29                             | 0.02154                                       | 170.0                              |                                   |   |                                    | 36.50                             | 0.04239                                       | 256.4                              |
| 21.21                             | 0.02268                                       | 170.3                              |                                   |   |                                    | 51.44                             | 0.05979                                       | 259.4                              |
|                                   |   |                                    |                                   |   |                                    | 61.78                             | 0.07247                                       | 261.9                              |

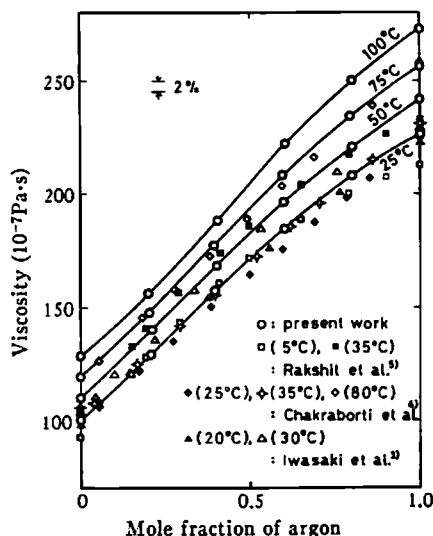


Fig. 3 Viscosity of argon-ammonia system at atmospheric pressure

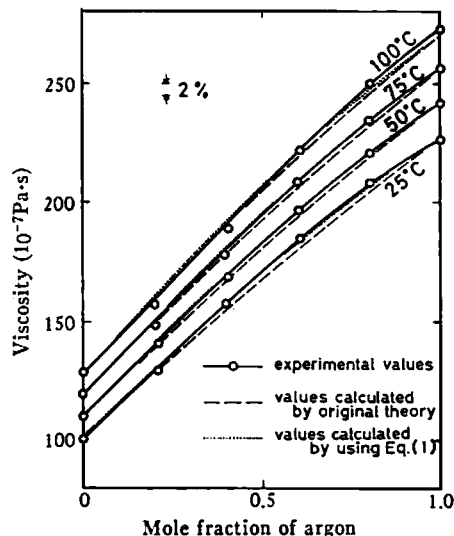


Fig. 4 Comparison of experimental value with original theoretical one and calculated one using Eq. (1) in argon-ammonia system

The viscosity values at atmospheric pressure ( $1.013 \times 10^5$  Pa) were determined in this work through the extrapolation of the viscosity vs. pressure curves to 1 atm, and are shown in Fig. 3 in comparison with the other investigations: by Iwasaki *et al.*<sup>3)</sup> (20 and 30°C), by Chakraborti *et al.*<sup>4)</sup> (25, 35, and 80°C), and by Rakshit *et al.*<sup>5)</sup> (5 and 35°C). The values obtained by Iwasaki *et al.*<sup>3)</sup> show the similar tendency with those obtained in this work, but those obtained by Chakraborti *et al.*<sup>4)</sup> are found to be roughly linear and those obtained by Rakshit *et al.*<sup>5)</sup> are seen to be more convex than those obtained in this work.

## Discussion

### Prediction of gas viscosity for nonpolar-polar mixtures by applying a correction factor

According to Chapman-Enskog's theory<sup>14)</sup>, the gas viscosity of a dilute binary mixture is given to the first approximation by Eq. (8.2-22) in Ref. 14. If the force constants of pure components are known, the viscosity of binary mixtures can be obtained theoretically. The Lennard-Jones potential function was applied for the nonpolar molecules and the Stockmayer potential function was done for the polar molecules. The force constants of argon were determined by use of the theoretical equation to the third approximation, Eq. (8.2-19) in Ref. 14, and the present experimental viscosity values at

14) J.O. Hirschfelder, C.F. Curtiss and R.B. Bird, "Molecular Theory of Gases and Liquids", John Wiley & Sons, Inc., New York (1954)

atmospheric pressure. The force constants obtained were as follows:

$$\text{Ar: } \sigma_n = 3.44_2 [\text{\AA}], \quad \epsilon_n/k = 116 [\text{K}]$$

where  $\sigma_n$  and  $\epsilon_n$  are the Lennard-Jones potential parameters. The theoretical viscosity of argon  $[\eta_1]_1$  required for the calculation of the viscosity of the binary mixtures  $[\eta_{m1x}]_1$  in Eq. (8.2-22) in Ref. 14 was calculated from Eq. (8.2-19) ( $k=3$ ) using its force constants presented above and that of ammonia  $[\eta_2]_1$  had been already calculated in Ref. 2. The force constants between nonpolar and polar molecules were obtained from the combining law, Eqs. (8.6-3) and (8.6-4) in Ref. 14. The theoretical viscosity values of the binary mixtures based on Chapman-Enskog's theory are shown by the dashed line, and the experimental values obtained in this work are denoted by the solid line in Fig. 4. As shown in this figure, the deviation of the theoretical values from the experimental ones is 2% at maximum.

In order to make the deviation smaller, a correction factor was introduced into the combining law as follows<sup>2)</sup>:

$$(\epsilon_{np}/k)' = \epsilon_{np}/k \{ (Z_{cn})^{1/2} + (Z_{cp})^{1/2} \}^{-2} \quad (1)$$

where  $\epsilon_{np}$  is a force constant between nonpolar and polar molecular interactions obtained from Eq. (8.6-4) in Ref. 14;  $k$  is the Boltzman constant; and  $Z_{cn}$  and  $Z_{cp}$  are critical compressibility factors of nonpolar and polar substances, respectively. The viscosity values of the gaseous mixtures obtained by applying Eq. (1) are shown by the dotted line in Fig. 4. Apparently the values calculated by using Eq. (1) agree better with the experimental ones than the original theoretical ones do in the argon-ammonia system, as well as in the hydrogen-ammonia system and in the nitrogen-ammonia system<sup>2)</sup>.

Table 3 Value of constants in Eq. (3)<sup>a)</sup>

| Temp. (°C) | $x_{Ar}$            | $\eta_0$ | $\alpha'$ | $\beta'$ | $\gamma' \cdot 10^{-1}$ |
|------------|---------------------|----------|-----------|----------|-------------------------|
| 25         | 0.000 <sup>b)</sup> | 101.0    | -3.58     | -169     | 1430                    |
|            | 0.208               | 129.5    | -0.379    | -64.2    | 488                     |
|            | 0.397               | 157.3    | 1.71      | -218     | 1050                    |
|            | 0.602               | 184.7    | 0.661     | 31.2     | 230                     |
|            | 0.800               | 208.1    | 0.414     | 16.1     | 39.2                    |
|            | 1.000               | 226.1    | 0.451     | 2.39     | 0.193                   |
| 50         | 0.000 <sup>b)</sup> | 110.4    | -2.80     | -8.53    | 268                     |
|            | 0.211               | 140.3    | -0.0321   | -14.1    | 90.5                    |
|            | 0.403               | 168.1    | 1.01      | -54.9    | 156                     |
|            | 0.600               | 196.3    | 0.730     | -8.77    | 24.3                    |
|            | 0.801               | 220.6    | 0.811     | -15.8    | 29.3                    |
|            | 1.000               | 241.9    | 0.394     | 2.46     | 0.188                   |
| 75         | 0.000 <sup>b)</sup> | 119.8    | -2.20     | 53.6     | -25.0                   |
|            | 0.202               | 148.0    | 0.0559    | 5.33     | 11.3                    |
|            | 0.394               | 177.4    | 0.551     | -4.62    | 17.8                    |
|            | 0.597               | 208.1    | 0.864     | -9.83    | 14.2                    |
|            | 0.794               | 234.4    | 0.537     | 3.66     | 4.65                    |
|            | 1.000               | 256.1    | 0.494     | 0.755    | 0.316                   |
| 100        | 0.000 <sup>b)</sup> | 128.9    | -1.03     | 27.3     | 1.71                    |
|            | 0.200               | 156.5    | -0.0876   | 18.7     | 5.83                    |
|            | 0.406               | 188.1    | 0.556     | 1.64     | 0.370                   |
|            | 0.603               | 221.9    | 0.893     | -10.8    | 13.0                    |
|            | 0.800               | 250.0    | 0.729     | 5.12     | 5.72                    |
|            | 1.000               | 272.9    | 0.430     | 1.72     | 0.123                   |

a)  $\eta = \eta_0(1 + \alpha'\rho + \beta'\rho^2 + \gamma'\rho^3)$   $\eta$ :  $10^{-7}$  Pa·s  $\rho$ :  $10^3 \text{ kg} \cdot \text{m}^{-3} = \text{g} \cdot \text{cm}^{-3}$

b) listed in Table 5 in Ref. 1

**Initial density dependence of the viscosity for argon-ammonia mixtures**

The viscosity of gases under pressures depends on pressure or density, and can be expressed in a power series expansion in density:

$$\eta = \eta_0 (1 + \alpha' \rho + \dots) \quad (2)$$

where  $\eta_0$  is the viscosity extrapolated to zero density and  $\alpha' = \eta_0^{-1} (\partial \eta / \partial \rho)_{\rho \rightarrow 0}$  denotes the initial density dependence of the viscosity<sup>1)</sup>. The viscosity of polar gases decreases with increasing pressure or density in lower temperature region, and after having a minimum increases with increasing pressure or density above a certain temperature. For polar gases, the decrease in viscosity is observed in the low pressure or density region below a certain temperature, that is, it is found that  $\alpha'$  is negative. In order to investigate the effect of argon concentration upon  $\alpha'$  of argon-ammonia mixtures, the gas viscosity was represented by a cubic equation of density as follows:

$$\eta = \eta_0 (1 + \alpha' \rho + \beta' \rho^2 + \gamma' \rho^3) \quad (3)$$

The constants in Eq. (3) were calculated from the experimental viscosity values by means of the least-squares method, and are listed in Table 3. The relation between  $\alpha'$  and the mole fraction of argon,  $x_{Ar}$ , at each temperature is shown in Fig. 5.  $\alpha'$  is almost constant above  $x_{Ar} = 0.6$ . Approximating three isothermal points in lower concentration region of argon with a straight line, each

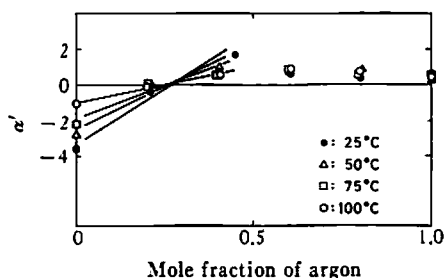


Fig. 5 Initial density dependence of argon-ammonia system

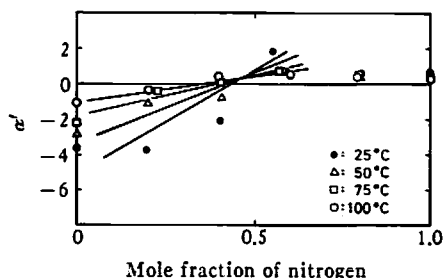


Fig. 6 Initial density dependence of nitrogen-ammonia system

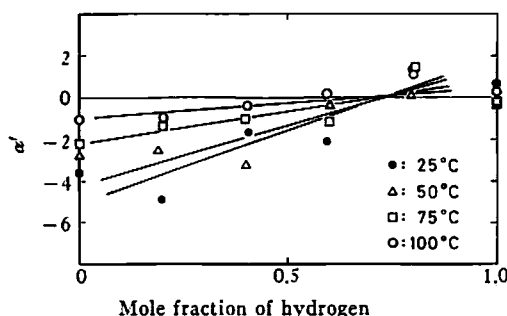


Fig. 7 Initial density dependence of hydrogen-ammonia system

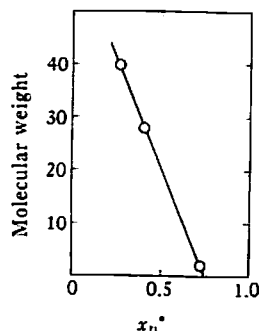


Fig. 8 Relation between molecular weight of nonpolar gas and  $x_n^*$

straight line and  $\alpha' = 0$  cross at the point  $x_{Ar} \approx 0.25$ , that is,  $x_{Ar}^* = 0.25$  where  $x_{Ar}^*$  is the mole fraction of argon at the point of intersection of straight lines across  $\alpha' = 0$ . The relation similar to Fig. 5 is shown in Figs. 6 and 7 for the nitrogen-ammonia system<sup>1)</sup> and for the hydrogen-ammonia system<sup>2)</sup>, respectively. Figure 6 shows that  $\alpha'$  is nearly constant above  $x_{N_2} = 0.8$ , and that  $x_{N_2}^*$  is about 0.4 in the nitrogen-ammonia system. Figure 7 shows that  $x_{H_2}^*$  is about 0.7 in the hydrogen-ammonia system. Thus, it is concluded that  $\alpha'$  increases with an increase in temperature and in mole fraction of nonpolar gases, and that the smaller the molecular weight of nonpolar gases is, the larger the  $x_n^*$  is, where the subscript n denotes a nonpolar gas. Figure 8 shows that an approximately linear relationship exists between the molecular weight of nonpolar gases and the  $x_n^*$ .

Polar gases show the initial decrease in viscosity below a certain temperature. Singh *et al.*<sup>15)</sup> discussed that the anomalous behavior of the viscosity of polar gases was ascribed to molecular association. Therefore, as described in the previous papers<sup>1,2)</sup>, Figs. 5~7 suggest that a rise in temperature and the presence of nonpolar molecules hinder molecular association of polar gases. Figure 8 shows that the larger the molecular weight of a nonpolar gas is, the smaller the  $x_n^*$  is. Namely, this figure suggests that the larger the molecular weight of a nonpolar gas is, the more strongly the nonpolar molecules hinder molecular association of polar substances.

The critical temperatures of the gaseous mixtures were determined by taking into account the mole fraction in place of the molecular weight of nonpolar gases, and correlated to  $\alpha'$ . The critical temperature of the mixtures was calculated by use of Chueh-Prausnitz's method<sup>16)</sup>.

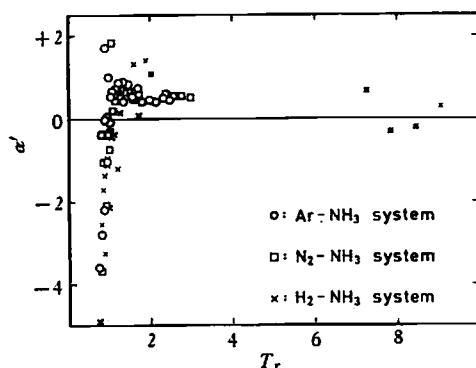


Fig. 9 Correlation between  $\alpha'$  and reduced temperature  $T_r$

$$T_{cm} = \sum_j \theta_j T_{cj} + \frac{\sum_i \sum_j \theta_i \theta_j \tau_{ij}}{\sum_j \theta_j} \quad (4)$$

$$\theta_j = x_j V_{cj}^{2/3} / \sum_j x_j V_{cj}^{2/3} \quad (5)$$

where  $T_{cm}$  is true mixture critical temperature,  $T_{cj}$  critical temperature of component j,  $\tau_{ij}$  an interaction parameter,  $x_j$  mole fraction of j, and  $V_{cj}$  critical volume of j. Figure 9 shows the

15) Y. Singh, S.K. Deb and A. K. Barua, *J. Chem. Phys.*, **46**, 4036 (1967)

16) R. C. Reid, J. M. Prausnitz and T. K. Sherwood, "The Properties of Gases and Liquids", Third Edition, McGraw-Hill Book Co., New York (1977)

correlation between  $\alpha'$  and the reduced temperature,  $T_r$ , where  $T_r = T/T_{cm}$ . In this figure, a similar tendency is observed for the three systems, and this pattern resembles the relations between the reduced second and third virial coefficients and the temperature reduced by the potential parameter<sup>14)</sup>.

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