The Viscosity of Ammonia: Experimental Measurements for the Dense Gaseous Phase and a Reduced State Correlation for the Gaseous and Liquid Regions

HIROSHI SHIMOTAKE and GEORGE THODOS

The Technological Institute, Northwestern University, Evanston, Illinois

The unsteady state flow of ammonia gas has been investigated to determine its viscosity at elevated pressures and moderate temperatures. This was accomplished in an experimental unit of the transpiration type which was calibrated with nitrogen, for which viscosity data at high pressures were available in the literature. To obtain the viscosity at the operating conditions the basic differential equation for the unsteady state flow caused by the experimental procedure was developed and solved with an IBM-650 digital computer.

Experimental runs were conducted for pressures ranging from 250 to 5,000 lb./sq. in. and temperatures from 100° to 200°C. This information has been used to establish the viscosity of ammonia at these dense phase conditions for which no viscosities had been previously reported. These values were used to develop a unique correlation between the residual viscosity and the density. This correlation then enabled the determination of ammonia's viscosity at the critical point $\mu_c = 2{,}395 \times 10^{-5}$ centipoises.

The Enskog viscosity equation has been used with the values resulting from this study and PVT data for ammonia to develop a relationship for the probability of nearness. This relationship enables viscosities to be calculated for densities up to 0.450 g./cc. which are in close agreement with the experimental values.

The area of transport properties is currently receiving considerable attention in the literature. Attempts have been made to utilize fragmentary experimental data to obtain extensive information on viscosity, thermal conductivity, and self-diffusivity. Relationships between the residual viscosity $\mu - \mu^*$ and density ρ have been developed by Shimotake and Thodos (*15*) for the inert gases and by Brebach and Thodos (*4*) for the diatomic gases. Using a similar approach Groenier and Thodos (*9*) investigated the behavior of the viscosity and thermal conductivity of ammonia in the dense phase region. In their viscosity study they found that the data of Carmichael and Sage (*5*) for the liquid region were internally consistent, but the viscosity values reported by Stakelbeck (*16*) and Kiyama and Makita (*12*) for the dense phase region scattered considerably. Because of these inconsistencies they were forced to utilize the Enskog relationship for viscosity (*7, 10*)

$$\frac{\mu}{\mu^*} = b\rho \left[\frac{1}{b\rho\chi} + \frac{4}{5} + 0.7614\, b\rho\chi \right] \tag{1}$$

to establish the dependence of residual viscosity on density for ammonia. Residual viscosities calculated from values resulting from Equation (1) appeared to follow a consistent pattern only at moderate densities. Therefore experimental viscosities for ammonia were determined for the dense phase and critical regions, for which reliable values were not previously available. This information is required for the establishment of the correct relationship between $\mu - \mu^*$ and ρ in the development of a reduced state viscosity correlation for ammonia.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

A schematic diagram of the equipment used for these viscosity studies is presented in Figure 1. This unit consisted of a transpiration type of viscometer and associated pressurizing, evacuating, temperature controlling, and pressure measuring facilities. The viscometer was composed of a U-tube manometer constructed of 316 stainless steel tubing and was provided with mercury in its legs.

The viscometer was mounted perpendicularly to a rotating shaft, which could tilt it on either side of a vertical axis. Stainless steel cross fittings attached to the two upper ends of the manometer contained electrode probes and enabled the joining of a spiral capillary tube and a bypass connection with the top of the U-tube. The electrode probes were made of solid tungsten wire, 0.068 in. in diameter, and were insulated with tightly fitting, soapstone cone connectors, which provided a gas-tight seal for pressures up to 10,000 lb./sq. in. The heights of the tips of the electrodes in the legs of the manometer differed by a distance of 1.588 cm. With the manometer placed in a vertical position the mercury level was adjusted to be somewhat above the tip of the longer electrode.

In a typical run the viscometer was charged with gas which had been sufficiently compressed in the pressurizing cell with mercury delivered from the volumetric pump. The manometer was then tilted approximately 20 deg. from the vertical axis with the bypass valve open. The bypass valve was then closed, and the U-tube was restored to its original vertical position, forcing the gas above the mercury to flow through the capillary tube. The time required for the mercury to lose contact with the shorter electrode, while a distance h_1 apart, and to make contact with the longer electrode, a distance h_2 apart, was recorded with an electric clock. This interval constituted the time of an experimental run.

The viscometer was located inside a constant air temperature bath constructed from insulating material and was heated electrically with strip heaters provided with radiation shields. The temperature was kept constant with a temperature recorder, which included a control unit. By circulating the air vigorously with a blower inside the temperature bath uniform temperature was maintained and a temperature control of 0.5°C. was possible. Pressures were measured with two Bourdon types of gauges having ranges of 0 to 5,000 and 0 to 18,000 lb./sq.in. The system was evacuated with a fore pump and a mercury diffusion pump connected in series.

MATHEMATICAL DEVELOPMENT

The pressure drop of an incompressible Newtonian fluid in isothermal laminar flow at steady state conditions through a circular capillary tube has

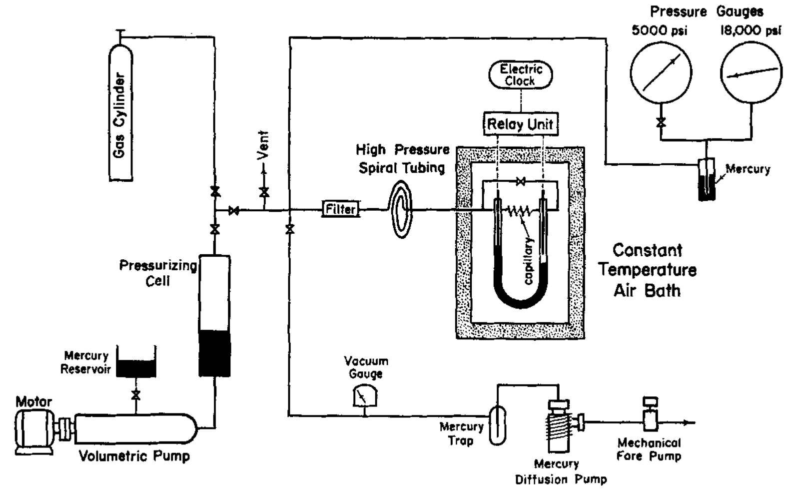

Fig. 1. Schematic diagram of experimental unit for high pressure viscosity studies.

been expressed by Hagen and Poiseuille as

$$\Delta P_c = \frac{8Q\mu L}{\pi r^4} \qquad (2)$$

Additional pressure drop contributions result from the sudden acceleration and deceleration of the fluid as it enters and leaves the capillary tube. These combined effects can be expressed in the relationship

$$\Delta P_i = m\frac{\rho_f Q^2}{\pi^2 r^4} \qquad (3)$$

The coefficient m has been calculated through theoretical considerations to be 1.08 by Schiller (*14*) and 1.12 by Boussinesq (*3*). Experimental studies (*1*) indicate that m can vary from 0.70 to 1.60. The present investigation found m to be 1.14 when the viscometer was calibrated with nitrogen under high pressures. The total pressure drop though the capillary tube follows from Equations (2) and (3):

$$\Delta P = \frac{8Q\mu L}{\pi r^4} + m\frac{\rho_f Q^2}{\pi^2 r^4} \qquad (4)$$

Equation (4) is applicable only to incompressible fluids. Gases at high pressures flowing through a capillary tube, in which the pressure drop is small, may be considered essentially incompressible. In the present study the maximum pressure drop was equivalent to 16 mm. of mercury, and therefore the gases, which were at high pressures, were treated as incompressible fluids.

The experimental procedure utilized to determine viscosity requires the development of an expression relating the time of a run to the corresponding difference in height h between the mercury levels in the U-tube. When the manometer is restored to its original position after having been tilted from the vertical axis, the quantity of fluid displaced from one side of the U-tube in a differential time $d\vartheta$ is

$$Qd\vartheta = -\pi R^2 d\left(\frac{h}{2}\right) \qquad (5)$$

The pressure drop across the capillary tube can be related to the mercury head difference in the U-tube as follows:

$$\Delta P = g(\rho_m - \rho_f)h \qquad (6)$$

When Equations (5) and (6) are substituted into Equation (4), the following differential equation results:

$$g(\rho_m - \rho_f)h = \frac{8\mu L}{\pi r^4}\left[-\frac{\pi R^2}{2}\frac{dh}{d\vartheta}\right] + m\frac{\rho_f}{\pi^2 r^4}\left[-\frac{\pi R^2}{2}\frac{dh}{d\vartheta}\right]^2 \qquad (7)$$

Equation (7) can be simplified to the following relationship:

$$\left[\frac{d\vartheta}{dh}\right]^2 + \frac{B}{h}\frac{d\vartheta}{dh} - \frac{C}{h} = 0 \qquad (8)$$

where B and C are constants for a particular experimental run

$$B = \frac{4R^2 L\mu}{g(\rho_m - \rho_f)r^4} \text{ and } C = \frac{mR^4\rho_f}{4g(\rho_m - \rho_f)r^4}$$

Although Equation (8) is nonlinear, it can be solved analytically with the following result:

$$\frac{d\vartheta}{dh} = -\frac{B}{2h} \pm \sqrt{\left(\frac{B}{2h}\right)^2 + \frac{C}{h}} \qquad (9)$$

Equation (9) may be readily solved by separating variables and integrating between the limits h_1 and h_2 to produce the desired relationship for ϑ:

$$\vartheta = \frac{B}{2}\ln\frac{h_1}{h_2} + \frac{B}{2}\ln\frac{(\sqrt{B^2+4Ch_2}+B)(\sqrt{B^2+4Ch_1}-B)}{(\sqrt{B^2+4Ch_2}-B)(\sqrt{B^2+4Ch_1}+B)} + [\sqrt{B^2+4Ch_1} - \sqrt{B^2+4Ch_2}] \qquad (10)$$

EXPERIMENTAL RESULTS

The viscometer was calibrated with experimental viscosities for nitrogen reported by Michels and Gibson (*13*) to establish the value of r, the average radius of the capillary tube. The basic constants for the viscometer used in this study were r = 0.01158 cm., L = 322.1 cm., R = 0.397 cm., and m = 1.14. By the use of these constants, viscosity values for nitrogen were calculated from Equation (10) and compared with the corresponding values resulting from the studies of Michels and Gibson (*13*), Iwasaki (*11*), and Brebach and Thodos (*4*). The resulting average deviation between these values was 0.8% indicating that this viscometer was capable of establishing viscosities of gases at high pressures with a good degree of precision.

Since the time of an experimental run and the quantities h_1, h_2, R, and L could be measured rather accurately, the chief sources of experimental error in the establishment of viscosities from Equation (10) arise from the uncertain reliability of the density values of the substance which is utilized and of the viscosity data for nitrogen used in the calibration of the viscometer. Although the accuracy of the viscosity values reported by Michels and Gibson (*13*) for nitrogen is not known, their experimental work is recognized to be of the highest quality and therefore their viscosities can be assumed to be quite accurate. The density values utilized in this investigation were obtained from a reduced state chart for ammonia (*8*) which reproduced experimental density data to within 0.78% by the use of the corresponding temperatures and pressures which could be measured to within 0.1%. The viscosity values for ammonia resulting from this study are therefore considered to be very dependable.

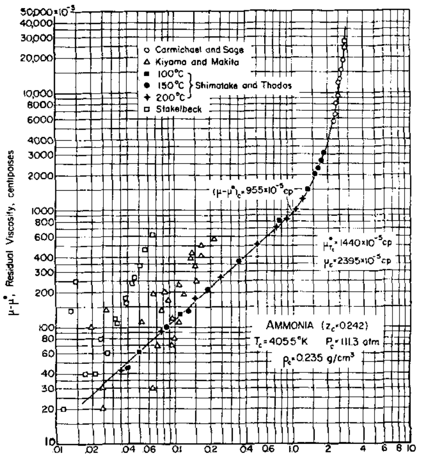

Fig. 2. Residual viscosity-reduced density relationship for ammonia in the gaseous and liquid phases.

Anhydrous ammonia, claimed to be 99.99% pure, was used in these studies. Experimental runs were conducted at the three temperature levels of 100°, 150°, and 200°C. and at pressures adjusted so that the ammonia always existed in the single phase region. The lengths of the experimental runs varied from 25 to 80 sec. The mercury head differences in the U-tube, h_1 and h_2, remained constant for each temperature level and are listed with the corresponding density as follows:

t, °C	h_1, cm.	h_2, cm.	ρ_m, g./cc.
100	1.778	1.397	13.3522
150	1.738	1.437	13.2330
200	1.706	1.469	13.1148

As the pressure of the gas was increased, the experimental run at each condition of temperature and pressure was repeated at least four times. After the highest pressure was reached, the pressure was decreased and each experimental run was repeated another four times. Therefore the results of each experimental run represent the average of at least eight independent determinations.

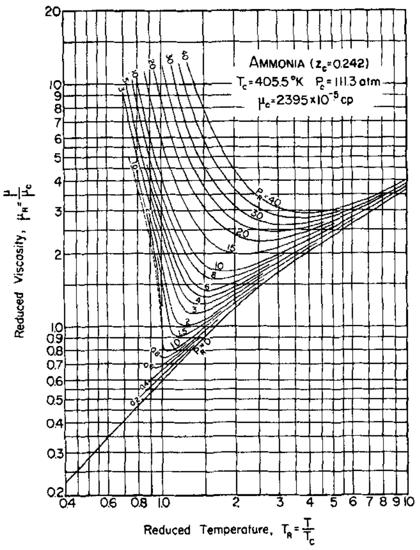

Fig. 3. Reduced state viscosity correlation for ammonia in the gaseous and liquid states.

The coefficient of the differential equation presented in Equation (8) $C = mR^4\rho_f/4(\rho_m - \rho_f)r^4$, requires that the density of the substance be available at the experimental conditions of temperature and pressure. The reduced state density correlation developed recently by Groenier and Thodos (*8*) for the gaseous and liquid states of ammonia was used in this investigation. The densities of ammonia corresponding to the experimental conditions are presented in Table 1.

In order to calculate the viscosity for the conditions of an experimental run, Equation (10) was programmed in an IBM-650 digital computer. Values of viscosity were assumed for each run and were used to produce the constant $B = 4R^2L\mu/g(\rho_m - \rho_f)r^4$, which was substituted with C into Equation (10) to calculate ϑ the duration of the experimental run. This procedure was continued by assuming viscosity values until the calculated values of ϑ agreed with the experimental values presented in Table 1. The viscosities which produced the agreement are reported in Table 1 for the conditions investigated.

TABLE 1. EXPERIMENTAL DATA AND VISCOSITY VALUES FOR AMMONIA AT HIGH PRESSURES

Run no.	ϑ, sec.	P, lb./sq. in. abs.	ρ, g./cc.	$\mu \times 10^4$, centipoise	$b\rho\chi$	b
			Temperature 100°C.			
1	28.6	250	0.0111	137	0.112	9.64
2	30.1	500	0.0259	144	0.230	7.99
3	32.0	750	0.0423	153	0.360	7.16
			Temperature 150°C.			
4	25.0	250	0.0094	155	0.077	7.91
5	26.6	500	0.0212	160	0.153	6.75
6	27.3	750	0.0306	164	0.230	6.72
7	28.5	1,000	0.0447	172	0.320	6.13
8	31.3	1,500	0.0823	188	0.520	4.87
9	38.9	2,000	0.181	232	0.900	3.28
10	51.0	2,500	0.324	300	1.27	2.41
11	60.3	3,000	0.374	354	1.50	2.41
12	65.0	3,500	0.397	381	1.60	2.40
13	71.0	4,000	0.417	415	1.78	2.44
14	75.0	4,500	0.428	438	1.95	2.41
15	79.0	5,000	0.440	461	2.05	2.41
			Temperature 200°C.			
16	23.1	250	0.00823	174	0.054	6.44
17	23.7	500	0.0176	179	0.108	5.91
18	24.2	750	0.0259	183	0.165	5.95
19	24.8	1,000	0.0353	187	0.230	5.89
20	26.0	1,500	0.0576	196	0.340	5.03
21	27.7	2,000	0.0846	209	0.435	4.22
22	29.3	2,500	0.118	220	0.570	3.70
23	32.3	3,000	0.169	242	0.715	3.05
24	34.0	3,500	0.209	254	0.830	2.71
25	36.3	4,000	0.250	270	0.950	2.47
26	39.6	4,500	0.287	294	1.07	2.37
27	42.4	5,000	0.315	314	1.21	2.31

INTERPRETATION OF DATA

The determined viscosities were subjected to a critical review to establish both their internal consistency and their agreement with viscosity values reported by other investigators (*5, 12, 16*) for liquid ammonia. For each run the residual viscosity $\mu - \mu^*$ was plotted against the corresponding reduced density ρ_R to produce the relationship presented in Figure 2. Viscosities for ammonia at normal pressures μ^* were obtained from the critical literature review of Groenier and Thodos (*9*). In that investigation they used the ten available references which reported experimental viscosity values for ammonia. The final viscosity values for ammonia at normal pressures used in this study are summarized as follows:

T_R	μ^*, centipoise	T_R	μ^*, centipoise
0.40	539 × 10^{-5}	1.50	2,190
0.50	682	2.00	2.860
0.60	825	3.00	3,990
0.70	978	4.00	4,880
0.80	1,125	6.00	6,280
0.90	1,270	8.00	7,580
1.00	1,440	10.00	8,770

The experimental results produced a single continuous relationship for the three temperatures investigated. The relationship of Figure 2 is applicable to ammonia in the gaseous, dense gaseous, and liquid phases. This relationship is linear for reduced densities up to $\rho_R = 1.0$ and can be expressed analytically as $\mu - \mu^* = 955 \times 10^{-5} \rho_R^{0.90}$. This behavior is consistent with the behavior established in viscosity studies for the inert and diatomic gases. The relationship resulting from this study, when extended, properly coincides with the curve produced by the viscosity data of Carmichael and Sage (*5*) and Stakelbeck (*16*) for liquid ammonia. In the gaseous region considerable disagreement exists between the values obtained in this investigation and those reported by Kiyama and Makita (*12*) and by Stakelbeck (*16*).

The critical viscosity of ammonia may be obtained directly from the relationship presented in Figure 2. The value of the residual viscosity at

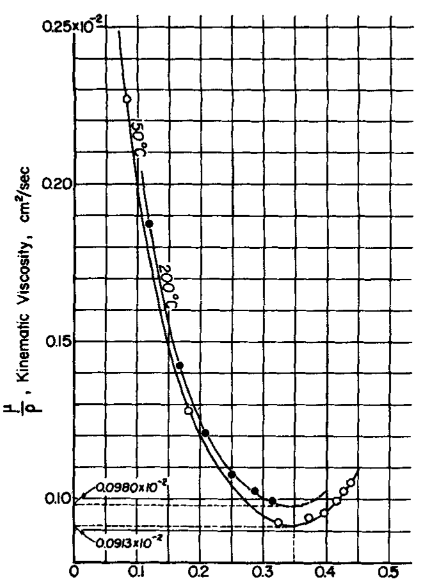

Fig. 4. Relationships between kinematic viscosity and density for ammonia at 150° and 200°C.

the critical point, $(\mu - \mu^*)_c = 955 \times 10^{-5}$ centipoises, and the corresponding value of the viscosity at normal pressures, ${}_{T_c}\mu^* = 1{,}440 \times 10^{-5}$ centipoises, establish the viscosity at the critical point to be $\mu_c = 2{,}395 \times 10^{-5}$ centipoises.

A complete reduced state correlation for the viscosity of ammonia has been developed from values of the viscosity at normal pressures and the residual viscosity relationship presented in Figure 2. In this development, the density compilation for ammonia presented by Groenier and Thodos (*8*) has been employed. This was accomplished by first selecting a number of density values covering the entire range of desired temperatures for the pressure of each isobar. The residual viscosity corresponding to each density was then obtained from Figure 2. With the corresponding values of μ^* viscosities were calculated for the selected temperatures of each isobar to produce the values which were divided by the critical viscosity and then plotted in Figure 3. Isobars constructed in this manner extend up to pressures of $P_R = 40$ and cover the temperature range $0.4 < T_R < 10$. This correlation is presented on reduced coordinates to permit comparisons with similar correlations developed for other substances.

APPLICATION OF ENSKOG THEORY

The experimental values obtained in this investigation were carefully analyzed with Enskog's theory to investigate the effect of pressure on the viscosity of ammonia. In order to use Equation (1), the Enskog equation for viscosity, it is necessary to obtain a relationship between $b\rho\chi$ and temperature and pressure. The quantity $b\rho\chi$ results from the Enskog equation of state

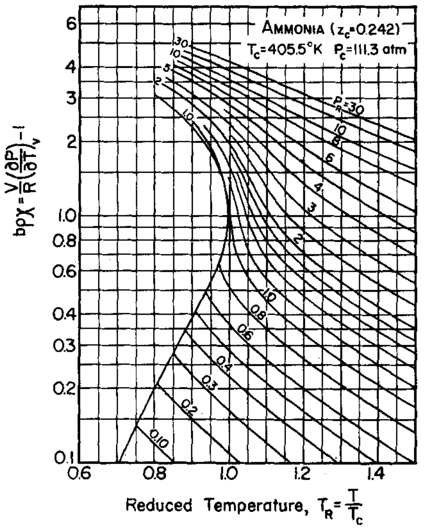

Fig. 5. Values of $b\rho\chi$ for ammonia in the gaseous and liquid states.

$$P + a\rho^2 = \frac{RT}{M}\rho\,[1 + b\rho\chi] \quad (11)$$

where a and b have been assumed by Enskog to be constants and χ is the probability of nearness for molecules in space. The quantity χ is equal to unity for a rare gas and approaches infinity as the density of the substance becomes very large. In 1899 Boltzmann and Clausius (*6*) developed the following relationship for the probability of nearness of a uniform gas composed of spherical molecules:

$$\chi = 1 + \frac{5}{8}b\rho + 0.2869\,(b\rho)^2 + \ldots \quad (12)$$

In order to obtain an expression for $b\rho$ Enskog differentiated Equation (11) with respect to temperature at constant volume and obtained the following relationship:

$$b\rho\chi = \frac{V}{R}\left(\frac{\partial P}{\partial T}\right)_V - 1 \quad (13)$$

The following expression for the kinematic viscosity can be obtained by rearranging Equation (1):

$$\frac{\mu}{\rho} = b\mu^*\left[\frac{1}{b\rho\chi} + \frac{4}{5} + 0.7614\,b\rho\chi\right] \quad (14)$$

The comprehensive theory of Enskog for the viscosity of compressed gases indicates that when μ/ρ is plotted against $b\rho\chi$ at constant temperature, a minimum value of the kinematic viscosity should result. Therefore Equation (14) can be differentiated with the assumption that b is constant, as follows:

$$\frac{d(\mu/\rho)}{d(b\rho\chi)} = b\,\mu^*\left[-\frac{1}{(b\rho\chi)^2} + 0.7614\right]$$

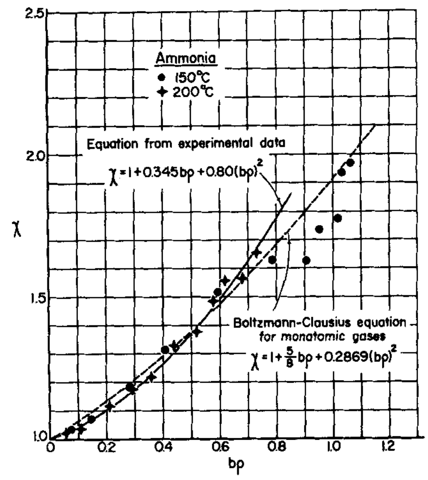

Fig. 6. Relationships between the probability of nearness and $b\rho$.

Since this derivative is equal to zero at the minimum kinematic viscosity

$$b\rho\chi = \sqrt{\frac{1}{0.7614}} = 1.146$$

$$\text{for } \left(\frac{\mu}{\rho}\right)_{\min}$$

An expression for the minimum kinematic viscosity at isothermal conditions may be obtained by substituting into Equation (14) the value $b\rho\chi = 1.146$ to produce the following relationship:

$$\left(\frac{\mu}{\rho}\right)_{\min} = 2.545\,b\mu^* \quad (15)$$

By combining Equations (14) and (15) the kinematic viscosity can be expressed as follows:

$$\frac{\mu}{\rho} = \frac{1}{2.545}\left(\frac{\mu}{\rho}\right)_{\min}\left[\frac{1}{b\rho\chi} + \frac{4}{5} + 0.7614\,b\rho\chi\right] \quad (16)$$

MINIMUM KINEMATIC VISCOSITY

Enskog's theory of the viscosity of compressed gases predicts that at isothermal conditions a minimum value of μ/ρ results when this quantity is plotted against $b\rho\chi$. Since $b\rho\chi$ can be related directly to density, it follows that a plot of μ/ρ against density should also produce a minimum value of the kinematic viscosity for each temperature. This behavior is illustrated in Figure 4 for temperatures of 150° and 200°C. for which adequate information was available. The minimum values of μ/ρ resulting for these temperatures were:

t, °C.	$(\mu/\rho)_{\min}$ sq. cm./sec.	ρ, g./cc.
150	0.0913×10^{-2}	0.35
200	0.0980×10^{-2}	0.35*

* Indicates approximate value.

Correlation for $b\rho\chi$

In order to obtain $b\rho\chi$ values from Equation (13) pressure-temperature isochors must be differentiated to produce the slopes $(\partial P/\partial T)_v$. By graphical means these slopes were produced from the density correlation for ammonia presented by Groenier and Thodos (8). These quantities and the corresponding density values permitted the calculation of $b\rho\chi$ for different conditions of temperature and pressure. A correlation of $b\rho\chi$ with reduced temperature for parameters of reduced pressure is presented in Figure 5. From this figure $b\rho\chi$ values are available for the gaseous and liquid states of ammonia for temperatures up to $T_R = 1.5$ and pressures up to $P_R = 40$.

The $b\rho\chi$ values obtained from Figure 5 and the minimum values of μ/ρ at 150° and 200°C. produced with Equation (16) viscosities that were not in agreement with the experimental values. Botzen (2) obtained similar inconsistencies in his high pressure thermal conductivity studies on nitrogen. These discrepancies indicate that the steps leading to the development of Equation (16) may not be completely justified and that the quantity b, which had been assumed to be constant at constant temperature, may be dependent on pressure.

Probability of Nearness, χ

Values of $b\rho\chi$ obtained from Figure 5 and the experimental viscosity values enabled the calculation of the quantity $b\rho$ from Equation (1). Values of $b\rho\chi$ and μ are included in Table 1 for the twenty-seven determinations of this study along with the resulting b values. The probability of nearness $\chi = b\rho\chi/b\rho$ follows directly from these quantities.

Values of χ are plotted vs. $b\rho$ in Figure 6, in which they are compared with values resulting from Equation (12) developed by Boltzmann and Clausius (6) for spherical molecules. Except for a few values in the high $b\rho$ range the points follow a trend that is somewhat different from the Boltzmann and Clausius relationship and which can be expressed analytically as follows:

$$\chi = 1 + 0.345\, b\rho + 0.800\, (b\rho)^2 \quad (17)$$

From Equation (1) viscosity values were calculated with Equation (17) and $b\rho\chi$ values obtained from Figure 5. These values were found to reproduce the experimental viscosities better than the values calculated in a similar manner with Equation (12). Both Equations (12) and (17) failed to permit the calculation of reliable viscosities for reduced densities of $\rho_R > 2.0$.

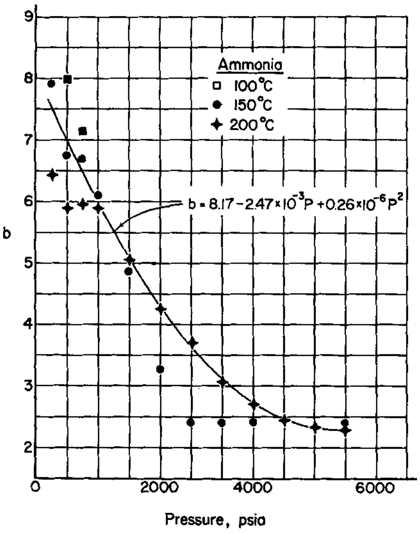

Fig. 7. Relationship between Enskog term b and pressure for ammonia.

Values of b were calculated from the established values of $b\rho$ and the corresponding densities and were plotted against pressure to produce the relationship presented in Figure 7. This figure indicates that b is not justifiably a constant and that therefore the development of Equations (13) and (16) is open to question. The relationship of Figure 7 can be expressed analytically as follows:

$$b = 8.17 - 2.47 \times 10^{-3} P + 0.26 \times 10^{-6} P^2 \quad (18)$$

where P is in pounds per square inch. Equations (17) and (18) were used with Equation (1) and with the values of the viscosity of ammonia at normal pressures to calculate the viscosity for the conditions of each experimental run. With the exception of a few viscosities at 150°C. the calculated values agreed well with the experimental viscosities.

ACKNOWLEDGMENT

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NOTATION

a, b = Enskog constants
B = $4R^2L\mu/g(\rho_m - \rho_f)r^4$
C = $mR^4\rho_f/4g(\rho_m - \rho_f)r^4$
g = acceleration constant, 980 cm./sec.^{2}
h = mercury head difference, cm.
h_1 = initial mercury head difference, cm.
h_2 = final mercury head difference, cm.
L = length of capillary, cm.
m = correction coefficient for kinetic energy term
M = molecular weight
P = pressure
P_c = critical pressure, atm.
P_R = reduced pressure, P/P_c
Q = volumetric flow rate, cc./sec.
r = radius of capillary, cm.
R = radius of U-tube, cm.
R = gas constant
T = temperature, °K.
T_c = critical temperature, °K.
T_R = reduced temperature, T/T_c
V = molar volume, cc./g.-mole

Greek Letters

ϑ = time, sec.
μ = viscosity, centipoises
μ^* = viscosity at normal pressures, centipoises
μ_c = critical viscosity, centipoises
μ_R = reduced viscosity, μ/μ_c
${}_{T_c}\mu^*$ = viscosity at critical temperature and normal pressure, centipoises
π = constant, 3.14159
ρ = density, g./cc.
ρ_c = critical density, g./cc.
ρ_f = density of fluid, g./cc.
ρ_m = density of mercury, g./cc.
ρ_R = reduced density, ρ/ρ_c
χ = probability of nearness of molecules

LITERATURE CITED

1. Barr, Guy, "A Monograph of Viscosity," pp. 22-23, Oxford University Press, London, England (1931).
2. Botzen, Albertus, "The Thermal Conductivity of Gases at High Pressures," Uitgeverij H. J. Paris, Amsterdam (1952).
3. Boussinesq, J., *Compt. rend.*, **113**, 9 (1891).
4. Brebach, W. J., and George Thodos, *Ind. Eng. Chem.*, **50**, 1095 (1958).
5. Carmichael, L. T., and B. H. Sage, *ibid.*, **44**, 2728 (1952).
6. Chapman, Sydney, and T. G. Cowling, "The Mathematical Theory of Non-Uniform Gases," 2 ed., p. 275, University Press, Cambridge, England (1958).
7. Enskog, David, *Kgl. Svenska Vetenskapsakad. Handl.*, **63**, No. 4 (1921).
8. Groenier, W. S., and George Thodos, *J. Chem. Eng. Data*, **5**, 285 (1960).
9. *Ibid.*, **6**, 240 (1961).
10. Hirschfelder, J. O., C. F. Curtiss, and R. B. Bird, "Molecular Theory of Gases and Liquids," p. 528, Wiley, New York (1954).
11. Iwasaki, Horoji, *Sci. Repts. Tohoku Univ.*, (A) **3**, 247 (1951).
12. Kiyama, Ryo, and Tadashi Makita, *Rev. Phys. Chem. Japan*, **22**, 49 (1952).
13. Michels, A., and R. O. Gibson, *Proc. Roy. Soc. (London)*, **A134**, 288 (1931).
14. Schiller, L., *Physik. Z.*, **23**, 14 (1922).
15. Shimotake, Hiroshi, and George Thodos, *A.I.Ch.E. Journal*, **4**, 257 (1958).
16. Stakelbeck, H., *Z. ges. Kälte-Ind.*, **40**, 33 (1933).

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