The Viscosity of Ammonia

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A new representation of the viscosity of ammonia is presented. The representative equations are based on a set of experimental data selected as a result of a critical assessment of the available information. The validity of the representation extends from 196 K to the critical temperature for both liquid and vapor phases. In the supercritical region the temperature range extends to 680 K for pressures at or below ambient and to 600 K for pressures up to 50 MPa. The accuracy of the representation varies from 0.5% for the viscosity of the dilute gas phase at moderate temperatures to about 5% for the viscosity at high pressures and temperatures. Tables of the viscosity generated by the correlating equation at selected temperatures and pressures and along the saturation line are presented to provide easy reference as well as for the validation of computer codes. © *1995 American Institute of Physics and American Chemical Society.*

Key words: ammonia; correlation; critical assessment; liquid viscosity; representation; vapor viscosity.

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1. Introduction

Ammonia is an important commercial fluid which ranks among the top ten bulk chemicals in terms of large-scale production. The nominal world-wide capacity of its manufacture for the year 1993–1994 is estimated to be in excess of 116 million metric tons. Owing to its large heat of vapor-

ization, ammonia originally found large-scale application as a refrigerant, particularly in commercial equipment, but the production and consumption for this purpose has been overshadowed in the recent past by its use in agricultural fertilizer production. However, the demand for environmentally friendly refrigerants seems likely to ensure that ammonia enjoys a resurgence of interest for use in refrigeration cycles as a pure fluid or in mixtures since it is neither a greenhouse gas nor a harmful agent to the ozone layer. Furthermore, recent developments indicate that a mixture of ammonia and water can be used as a working fluid in power plants with resulting improved thermodynamic performance. In any of its industrial applications a knowledge of the thermophysical properties for the fluid over a wide range of temperatures and pressures is required, preferably in a machine-usable format.

Most of the studies of the transport properties of pure substances have been confined to nonpolar materials. Ammonia is a polar substance with a significant dipole moment which confers on the fluid a behavior that differs substantially from that of nonpolar substances. Although several assessments[1-4] of the viscosity of ammonia have been made in the past, none of these treatments has included equations for the representation of the property in the dense fluid region. Using the limited data available to them in 1961, supplemented by estimated values, Groenier and Thodos[1] developed generalized graphical correlations for the viscosity of the gas at moderate pressures and for the fluid in the dense phase region. The ASHRAE publication[2] on the thermophysical properties of refrigerants gives representative equations only for the temperature dependence of the viscosity of the gas at atmospheric pressure and for the saturated liquid. The most comprehensive assessment to date is that of Golubev et al.[3] in 1978. Using the data available to them at that time, they derived, largely using graphical techniques, tables of the viscosity within the temperature range 200 to 750 K and the pressure range 0.1 to 50 MPa. Using similar graphical smoothing techniques, Stephan and Lucas[4] produced in 1979 tables of the viscosity of ammonia in the temperature range 310 to 600 K and pressure range 0.1 to 60 MPa.

This paper contains a correlation of the viscosity data for both gaseous and liquid ammonia based on a critical assessment of all published experimental measurements including those which have most recently become available. A correlating equation is obtained which represents the most reliable sets of data within their estimated uncertainty over a wide range of temperature and pressure, and which reproduces the known phenomenological behavior of this polar fluid. The representative equation is applicable in the temperature range from the triple point to almost 700 K and in the pressure range from the triple point pressure to 50 MPa. In order to make use of the representation of the viscosity which is written in terms of the temperature and the density, it is necessary to make use of an equation of state. In this work we have consistently employed the equation of state of Tillner-Roth et al.[5] for all the thermodynamic properties of ammonia.

The analysis presented in the following sections conforms closely to that adopted in earlier work[6,7] on the representation of the transport properties of fluids.

2. Equation of State

The proposed representation of the viscosity of ammonia expresses the viscosity as a function of density and temperature for reasons associated with the kinetic theory. In practice, the majority of experimental viscosity measurements are reported at specified pressures and temperatures, thus the use of an accurate equation of state is essential. The thermodynamic formulation for ammonia used here was the analytic equation developed by Tillner-Roth et al.[5] The equation is applicable in the range extending from the triple point temperature to 680 K and for the pressure range extending from the dilute gas to 500 MPa. Temperatures in the Tillner-Roth et al.[5] formulation are expressed in terms of the temperature scale ITS-90. The equation of Tillner-Roth et al.[5] is preferred to the earlier equation of Haar and Gallagher[8] partly because it contains fewer terms and is therefore easier to use, but largely because it provides improved consistency with the equation of state for the critical region which will be important in the treatment of the thermal conductivity of ammonia subsequently.

In point of fact, in the context of the viscosity alone, the equation of state of Haar and Gallagher[8] could be used to evaluate the density of ammonia and employed in conjunction with the present representation of the viscosity without incurring an error beyond the uncertainty ascribed to the correlation. However, it should be emphasized that in this case temperatures measured on the ITS-90 temperature scale should be converted to the earlier IPTS-68 scale before the equation of state of Haar and Gallagher[8] is used to evaluate the density.

3. Experimental Viscosity Data

3.1. Sources of Data

The dynamic viscosity of ammonia in the liquid and gaseous states have been the subject of study by many investigators. A literature survey reveals about forty experimental determinations dating from the early work of Graham in 1846.[9] The data sources are listed in Table 1 together with details of the method of measurement, the fluid phase investigated, and the range of experimental conditions for each study. Though the measurements appear to span a wide range of temperatures (from 196 to 989 K) there are large regions of the pressure/temperature plane which are either devoid of data or for which the coverage is sparse as depicted by Fig. 1. The liquid region below 300 K and up to the critical pressure is not adequately covered. No data are available in the supercritical fluid phase above 600 K and at pressures higher than 0.1 MPa. The supercritical region above 523 K and at pressures higher than the critical pressure is not covered by any data; the region below 200 K has equally not been investigated. In addition, as already established by the previous assessments of the data, the agreement between the measurements of viscosity reported by the different investigators is not good.
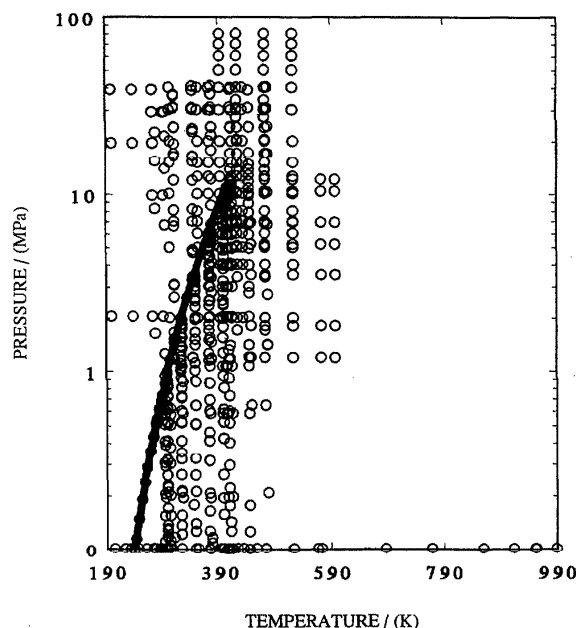
FIG. 1. Distribution of the available experimental viscosity data of ammonia. The full line shows the saturation line.

3.2. Data Selection and Adjustment

A critical analysis of the data has been carried out in order to determine a primary data set. Ideally, for a set of measurements to qualify for the primary class, it should have been obtained from a high precision instrument for which there is a full working equation. In practice, these constraints had to be relaxed by inclusion of other data which did not meet the stringent ideal conditions in order to cover as much as possible of the phase space. In such cases, the weights assigned to the results were adjusted according to an ascribed uncertainty. Graphical examination of the data was also used to provide a check on consistency and precision. Major discrepancies were occasionally observed between overlapping sets of data from different authors. In each case a careful examination of the experimental method was employed to select the most reliable set of data. The primary data set established in this manner[10–20] is employed in the development of the representative equation for the viscosity of ammonia, whereas the secondary data are used for comparison purposes only.

The majority of the primary set of experimental data was obtained from methods using either an oscillating disc or a capillary flow apparatus. Detailed studies of the theory and mechanics of operation of these instruments[21,22] indicate that both are now well understood. It was found necessary to supplement these data by a number of other data sets. A major source of data of ammonia by Carmichael et al.[12] was obtained using a rotating cylinder viscometer, for which a mathematical theory for the correction of end effects has not yet been developed. The uncertainty introduced by the lack of a rigorous theory limits the absolute nature of this method and impairs the accuracy. Measurements obtained from such an apparatus must be considered of lower accuracy than

TABLE 1. List of experimental sources of data on the viscosity of ammonia.

Author(s)	Year (Ref.)	Method	Region[a]	T(K)	P(MPa)
Graham	1846 (9)	capillary	g	273–298	~0.1
Fitzgerald	1912 (66)	capillary	l	240	~0.1
Vogel	1914 (19)	oscillating disc	g	196–273	~0.1
Elsey	1920 (67)	capillary	l	240	~0.1
Rankine and Smith	1921 (27)	capillary	g	373	~0.1
Edwards and Worswick	1925 (56)	capillary	g	288–457	~0.1
Jung and Schmick	1930 (78)	capillary	g	288	~0.1
Braune and Linke	1930 (18)	oscillating disc	g	294–714	~0.1
Fredenhagen	1930 (63)	capillary	l	204–240	~0.1
Trautz and Heberling	1931 (20)	capillary	g	291–989	~0.1
Monoszon and Pleskov	1932 (75)	capillary	l	223–293	0.1–0.8
Stakelbeck	1933 (68)	falling cylinder	gl	253–353	0.1–2.9
Van Cleave and Maass	1935 (28)	oscillating disc	g	202–297	~0.1
Planck and Hunt	1939 (61)	capillary	l	278–298	0.5–1.0
Wobser and Müller	1941 (69)	rolling ball	g	293–371	~0.1
Pinevich	1948 (70)	capillary	l	247–323	0.1–2.0
Shatenshtein et al.	1949 (62)	capillary	l	288–298	0.7–1.0
Kiyama and Makita	1952 (71)	rolling ball	g	323–573	0.1–9.7
Carmichael and Sage	1952 (72)	rolling ball	l	278–378	0.9–41
Golubev and Petrov	1953 (64)	capillary	gl	303–523	0.1–81
Carmichael et al.	1963 (12)	rotating cylinder	gl	311–478	0.1–41
Shimotake and Thodos	1963 (73)	capillary	g	373–473	1.7–34
Krynicki and Hennel	1963 (60)	capillary	l	273–343	0.4–3.3
Iwasaki et al.	1964 (11)	oscillating disc	g	293–303	0.1–0.6
Chakraborti and Gray	1965 (29)	capillary	g	298–353	~0.1
Burch and Raw	1967 (17)	capillary	g	273–673	~0.1
Pal and Barua	1967 (58)	oscillating disc	g	306–479	~0.1
Pal and Barua	1967 (76)	oscillating disc	g	297–473	~0.1
Pal and Barua	1967 (74)	oscillating disc	g	306–469	~0.1
Iwasaki and Takahashi	1968 (16)	oscillating disc	g	298–408	0.1–9.3
Pal and Bhattacharyya	1969 (55)	oscillating disc	g	299–373	~0.1
Bhattacharyya et al.	1970 (57)	oscillating disc	g	218–309	~0.1
Makhija and Stairs	1970 (15)	capillary	l	208–238	~0.1
Golubev and Sharapova	1971 (65)	capillary	l	200–291	~2.0–39.3
Rakshit et al.	1973 (59)	oscillating disc	g	238–308	~0.1
Rakshit and Roy	1974 (77)	oscillating disc	g	238–308	~0.1
Golubev and Likhachev	1974 (14)	capillary	g	294–444	0.1–14.8
Hongo and Iwasaki	1977 (10)	oscillating disc	g	298–373	0.1–6.0
Sun and Storvick	1979 (13)	capillary	g	448–598	0.6–12.2
Wakao and Nagashima	1993 (31)	oscillating cylinder	l	203–294	~0.9

[a]In the above "g" refers to the gaseous state, "l" to the liquid state, either subcooled or saturated and "gl" to both the gaseous and the liquid state and "~" indicates at or below 0.1 MPa.

those from the more rigorously established techniques. How-ever, the data of Carmichael et al.[12] were compared with those of other authors in regions of overlapping fluid states. Good agreement was found between the data of Carmichael et al.,[12] the later measurements of Golubev and Likhachev[14] and the more recent values reported by Sun and Storvick[13] using a capillary flow viscometer along two high temperature isotherms, as will be shown later in the discussion. Although the data agreed to within the claimed accuracy of the two methods, it was noted that Carmichael et al.[12] and Golubev and Likhachev[14] observed an initial decrease in viscosity along an isotherm with increasing density whereas this was not apparent in the measurements of Sun and Storvick.[13] Likewise at low temperatures, the measurements of Car-michael et al.[12] are consistent with the remainder of the pri-mary set of data within the estimated uncertainty. The agree-ment thus observed with the results of measurements with more widely used and established techniques suggests that

the rotating cylinder measurements of Carmichael et al.[12] are accurate to within their assessed uncertainties of 2 percent. All the data of Carmichael et al.[12] were therefore included in the primary set except those on the 410.91 K isotherm which were excluded on account of their closeness to the critical temperature.

A number of the published measurements on the viscosity of ammonia have been obtained in a relative manner using the values of the viscosity of other fluids as calibration data. In each of these cases the source and reliability of the cali-bration values used have been checked against current recommendations[23–26] and adjusted as necessary. Only five sets of data required re-normalization in this way. For three of these, belonging to the secondary set, the magnitude of the re-normalization involved was small[27–29] and of the order of one percent; however, for two[17,20] the adjustment required was more substantial. The data of Burch and Raw[17] which span a large temperature range (273–673 K) in the dilute gas

region were judged to be important for the development of the zero-density correlation. However, these measurements were made relative to the results of Trautz and Heberling[20] for nitrogen. It is now firmly established that the measurements of Trautz and co-workers in the 1930's are in systematic error and differ from recent accurate measurements of viscosity in a roughly linear fashion with temperature, the difference rising to some 4% to 5% at 1000 K.[23,24,30] The values of Trautz and Heberling[20] for ammonia were scaled by comparing their reported values for nitrogen and oxygen with the currently accepted values[23,24,26] for these fluids. The correction applied amounted to some +5 percent at the highest temperature of measurement. Burch and Raw's measurements[17] were therefore scaled in a similar manner and found then to be consistent with the results of other workers in a region of overlap. Above about 723 K, the values reported by Trautz and Heberling[20] are not reliable due to ammonia decomposition into hydrogen and nitrogen. The rate of decomposition increases with temperature and is considerably affected by the catalytic nature of the materials with which the gas comes into contact.

For the liquid phase, there is a paucity of reliable data. Only the data of Carmichael et al.[12] and Makhija and Stairs[15] were judged to be sufficiently accurate to be included in the primary set. Near the completion of the present work, new data on the saturated liquid by Wakao and Nagashima[31] were communicated to us. Because not all of the details of the measurements were available, we have been able to include the data only in our final comparisons rather than in the construction of the representation.

Additional checks were made on the sources and reliability of any ancillary data, such as the density, required in the analysis of the experimental viscosity data. Although different sources of density data have been used by various authors, no major differences were found which justified any modification of the reported values of viscosity. The values of temperature recorded in the selected works were corrected where necessary to the ITS-90 scale.[32-34]

The list of sources of primary experimental data used for the development of both the zero-density correlation and the excess viscosity contribution is presented in Table 2 which includes also estimated uncertainties on the data. The assigned accuracy for each source is based on the measurement method used, the quoted experimental errors and the extent of consistency with other independent data in overlapping regions. In certain cases, the ascribed accuracies were adjusted according to temperature range, with higher uncertainties given to higher temperature data.

4. Methodology

For theoretical as well as practical reasons, the viscosity is usually decomposed into three contributions:[6,35]

$$\eta(\rho,T) = \eta_0(T) + \Delta\,\eta(\rho,T) + \Delta\,\eta_c(\rho,T) \qquad (1)$$

or

$$\eta(\rho,T) = \bar{\eta}(\rho,T) + \Delta\,\eta_c(\rho,T), \qquad (2)$$

TABLE 2. List of experimental sources of viscosity data used in the analysis.

Author(s)	Ref.	No. of points accepted	Estimated uncertainty %
Primary data			
Vogel	19	2	2.0–3.0
Braune and Linke	18	9	1.5
Trautz and Heberling	20	4	2.0–10.0
Carmichael et al.	12	140	2.0–4.0
Iwasaki et al.	11	20	0.5
Burch and Raw	17	11	1.5
Iwasaki and Takahashi	16	106	0.5–1.5
Makhija and Stairs	15	20	1.0
Golubev and Likhachev	14	116	2.0–3.0
Hongo and Iwasaki	10	62	0.5–0.75
Sun and Storvick	13	35	2.0
Secondary data			
Rankine and Smith	27	1	2.0
Edwards and Worswick	56	3	2.5
Fredenhagen	63	2	5.0
Trautz and Heberling	20	24	2.0–10.0
Monoszon and Pleskov	75	6	5.0–10.0
Van Cleave and Maass	28	9	5.0
Plank and Hunt	61	3	3.0
Shatenshtein et al.	62	3	3.0
Golubev and Petrov	64	122	10.0
Carmichael et al.	12	37	2.0–4.0
Krynicki and Hennel	60	8	1.5
Chakraborti and Gray	29	3	1.5
Pal and Barua	58	5	1.0–2.0
Pal and Bhattacharyya	55	3	2.0
Bhattacharyya et al.	57	5	2.0
Golubev and Sharapova	65	14	10.0
Rakshit et al.	59	4	1.0–2.0
Wakao and Nagashima	31	19	4.0

where $\eta_0(T)$ is the viscosity in the zero-density limit, $\Delta\,\eta(\rho,T)$ an excess viscosity which represents the increase in the viscosity at elevated density over the dilute gas value at the same temperature, and $\Delta\,\eta_c(\rho,T)$ a critical enhancement accounting for the increase in viscosity in the immediate vicinity of the critical point. The two first terms in the right-hand side of Eq. (1) are sometimes grouped together and the resulting quantity is then termed the background contribution $\bar{\eta}(\rho,T)$. In the development of the viscosity correlation, this approach allows an independent treatment of each contribution in the light of available experimental and theoretical information. Indeed, the use of the most recent advances in kinetic theory helps to assess the internal consistency of the various sources of experimental data.

4.1. Viscosity in the Zero-Density Limit

The viscosity of a fluid in the zero-density limit, $\eta_0(T)$, being an experimentally accessible quantity, is amenable to analysis independently of the influence of the other contributions enumerated in Eq. (1). Moreover, the existence of a well-developed kinetic theory[36] applicable under the dilute gas condition offers some guidance as to the form of the correlation. Indeed, in the zero-density limit, the viscosity is almost independent of the existence of internal degrees of

freedom, and hence is almost unaffected by inelastic collisions. However, despite the availability of a detailed theory of the viscosity in the zero-density limit, it cannot be used for the prediction of the viscosity with an accuracy comparable with that of experiment owing to our incomplete knowledge of the intermolecular potential for ammonia. Therefore, the zero-density values have to be extracted from the experimental data themselves.

The examination of the experimental data reveals a lack of useful data in the real limit of zero density. For reasons that will become clear, it is important to distinguish the property in the true limit of zero density from use at low pressures (such as 0.1 MPa). The lack of data in this vitally important region means that they must be first extracted from the available experimental data. The experimental viscosity values[10-14,16] measured along isotherms were fitted to polynomials in density following as far as possible the criteria recommended by Hanley *et al.*[37] The fits yielded both the zero-density values as well as the first-density coefficients for the thirty isotherms considered. The isotherms reported by Hongo and Iwasaki,[10] Iwasaki *et al.*,[11] Carmichael *et al.*,[12] Golubev and Likhachev,[14] Sun and Storvick,[13] and Iwasaki and Takahashi[16] which cover the temperature range 293–598 K were used in the analysis. In order to extend the temperature range, the set of zero-density values obtained was supplemented by the addition of the data of Braune and Linke,[18] Burch and Raw,[17] and Vogel.[19] The data from these sources have an associated uncertainty somewhat larger than the bulk of the data available at intermediate temperatures. However, since they are the only data sets available at low and high temperatures, they were included in the fitting procedure with an appropriate weight. Moreover, since the sets of measurements were performed at pressures below 0.1 MPa, no attempt was made to extrapolate the values at particular temperatures to the limit of zero density since the differences involved are substantially less than the experimental uncertainty. One datum from the set of Vogel[19] was measured at 196 K and proved therefore useful for defining the zero-density viscosity near the triple point temperature of ammonia (195.48 K). For extrapolation purposes up to 953 K, four data points belonging to the scaled set of Trautz and Heberling[20] were included in the fit but with a high uncertainty of 10%. Altogether 56 data points were used to develop the zero-density correlation.

The kinetic theory of dilute gases relates the viscosity of a pure gas to an effective collision cross section which contains all the dynamical and statistical information about the binary collision. This relationship, for practical purposes, can be written in the form

$$\eta_0(T) = \frac{0.021357[TM]^{1/2}}{\sigma^2 \mathfrak{S}_\eta^*},$$ (3)

where $\mathfrak{S}_\eta^*$ is a reduced effective collision cross section, T is the temperature in kelvin, M is the relative molecular mass, σ is a length scaling parameter in nm, and $\eta_0(T)$ is the viscosity in the limit of zero density expressed in units of μPa·s.

The reduced effective collision cross-section values corresponding to the viscosity values in the limit of zero density

TABLE 3. Coefficients for the representation of the effective collision cross section of ammonia with Eq. (4).

i	a_i
0	4.99318220
1	−0.61122364
2	0
3	0.18535124
4	−0.11160946

with $\epsilon/k = 386$ K, $\sigma = 0.2957$ nm, and $M = 17.03026$

were calculated with the help of Eq. (3). The resulting effective collision cross-section values were then fitted, by means of statistical weights derived from experimental uncertainties as explained earlier, to the functional form,

$$\ln \mathfrak{S}_\eta^* = \sum_{i=0}^{4} a_i(\ln T^*)^i,$$ (4)

where the reduced temperature T^* is given by

$$T^* = kT/\epsilon$$ (5)

and ϵ/k is an appropriate energy scaling parameter in kelvin.

It has been found that the primary viscosity data of ammonia in the limit of zero density can be represented, within their estimated uncertainties, by means of Eqs. (3)–(5), the optimum coefficients a_i and the parameters σ and ϵ. These latter two parameters are, in principle, arbitrary, and the values adopted are discussed in Section 4.4. Table 3 contains the relevant coefficients for the representation of the zero-density viscosity values of ammonia. The resulting correlation is valid in the temperature range from 196 to 714 K, and its uncertainty is estimated to be ±0.5% in the temperature interval 273–500 K, ±1.5% from 500 to 714 K and ±2% below 273 K. Figure 2 illustrates the deviations of the zero density and low pressure viscosity values from the calculated ones using the correlation. It shows that all the data are represented by the zero-density correlation within their ascribed uncertainties.

4.2. Viscosity in the Critical Region

Theoretical and experimental evidence indicates that the viscosity of fluids diverges at the critical point.[38] However, unlike the critical enhancement in thermal conductivity, that in viscosity is much less pronounced and is restricted to a much narrower range of conditions around the critical point. For a number of fluids,[6,7] it has been found that the ratio of $\Delta \eta_c(\rho,T)/\eta(\rho,T)$ is greater than 0.01 only within 1% (~4 K) of the critical temperature. Owing to the complete absence of experimental data for the viscosity of ammonia in the region around the critical point ($\rho_c = 225.0$ kg/m^3, $T_c = 405.4$ K, $P_c = 11.3334$ MPa), it has not been possible to establish the form of the enhancement term, $\Delta \eta_c(\rho,T)$, of Eq. (1). Throughout the remainder of this article, the viscosity should therefore be identified with the normal or background viscosity defined by Eq. (1).
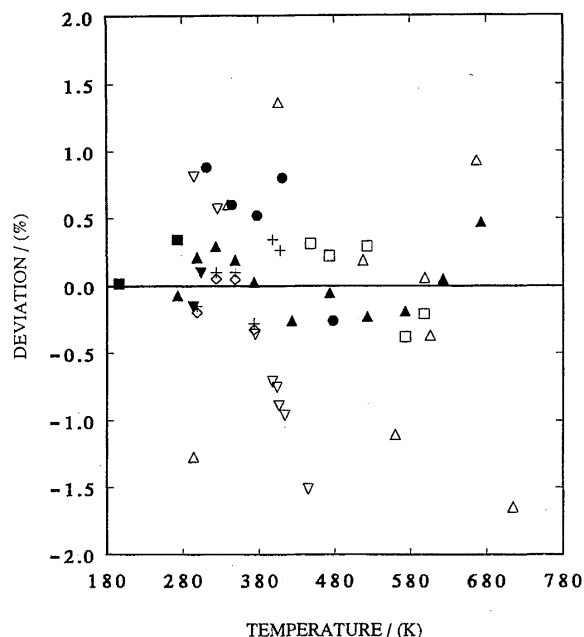
FIG. 2. Deviations of the extracted zero-density and low pressure viscosity data from the present correlation expressed by Eqs. (3) to (5). The deviations are defined as: $100(\mu_{exp} - \mu_{cal})/\mu_{exp}$. ■ Vogel;[19] + Iwasaki and Takahashi;[16] ▼ Iwasaki et al.;[11] □ Sun and Storvick;[13] ◊ Hongo and Iwasaki;[10] ▽ Golubev and Likhachev;[14] ● Carmichael et al.;[12] ▲ Burch and Raw;[17] △ Braune and Linke[18].

4.3. Excess Viscosity

The excess viscosity contribution describes how the viscosity of the fluid behaves as a function of density outside of the critical region. The present state of knowledge does not provide a satisfactory theory for the excess viscosity over the whole phase space. However, in practice, a power series expansion in density for the representation of the excess viscosity has often been found to be adequate.[6,39-41] The series adopted is of the following form:

$$\Delta\eta(\rho,T) = b_1(T)\rho + \Delta_h\eta(\rho,T) = b_1(T)\rho + \sum_{i=2}^{n} b_i(T)\rho^i,$$

(6)

where $b_i(T)$ are empirical functions of temperature. From observations on a number of fluids[35] it appears that, for supercritical temperatures, the coefficients $b_i(T)$ are often very weak functions of temperature. However, for the first coefficient $b_1(T)$, recent theoretical work[35,42-45] has established a temperature dependence which can be quite marked at subcritical temperatures. Indeed, the coefficient $b_1(T)$ can change sign from positive to negative as the temperature is reduced. Thus, the viscosity in the vapor phase along an isotherm may first decrease owing to a negative value of $b_1(T)$ and subsequently increase owing to the influence of higher order terms as the density increases. This effect has been observed for a number of fluids.[46,47] Thus, in order to obtain an accurate representation of the behavior of the viscosity in the vapor phase, the temperature dependence of the first density coefficient of viscosity must be taken into consideration.

4.4. Initial Density Dependence

The viscosity of ammonia vapor at temperatures up to around the critical temperature has a negative pressure coefficient similar to that found for steam.[25,48] This phenomenon was first observed by Iwasaki et al.[11] using an oscillating disc viscometer and subsequently confirmed by other workers using both oscillating disc and capillary flow viscometers.

As was remarked earlier, a statistical analysis of the primary data employed for the evaluation of the zero-density values of viscosity also provided experimental values of the first-density coefficient $b_1(T)$. The values of this coefficient were then expressed in terms of the second viscosity virial coefficient $B_\eta(T)$ by means of the definition,

$$b_1(T) = B_\eta(T)\,\eta_0(T)$$

(7)

using experimental values of $\eta_0(T)$.

As a result of both theoretical and experimental studies of the second viscosity virial coefficient, it has been possible to develop a valuable corresponding-states representation of its behavior as a function of temperature.[45,49] This proposed model has been useful for treating noble gases, simple gases such as n-alkanes[50] and aromatic vapors.[51] Vogel et al.[52] have shown that polar as well as nonpolar gases exhibit the same general behavior of $B_\eta(T)$ as a function of reduced temperature.

The existence of a model for the second viscosity virial coefficient offers the opportunity of confirming the validity of some of the experimental data as well as of extending its temperature range. For that reason, we have used the model of Rainwater and Friend[49] as modified by Bich and Vogel[53] to examine the experimental values of $B_\eta(T)$ deduced from analysis of the primary experimental data. The model of Rainwater and Friend[49] is based upon the behavior of a gas whose molecules interact according to a Lennard-Jones (12-6) potential. It therefore predicts that for all such gases the reduced second viscosity virial coefficient, for practical applications, is defined by[6]

$$B_\eta^*(T) = \frac{B_\eta}{0.6022137\sigma^3},$$

(8)

where B_η is in units of $l \cdot mol^{-1}$.

The reduced second viscosity virial coefficient is a universal function of T^* and has been represented by Bich and Vogel[53] by the empirical function

$$B_\eta^* = \sum_{i=0}^{n} c_i(\sqrt{T^*})^{-i}$$

(9)

with the coefficients c_i given in Table 4 for completeness.

Accordingly we have determined the parameters σ and ϵ/k which secure the optimum representation of the experimental values of $B_\eta^*(T)$ by means of this function. Figure 3 compares the theoretical and experimental values and serves to confirm that the qualitative values predicted by theory are reproduced by the available experimental data, in particular the change of sign of the coefficient.

TABLE 4. Coefficients for the initial density dependence, Eq. (9).

i	c_i
0	-0.17999496×10^1
1	0.46692621×10^2
2	-0.53460794×10^3
3	0.33604074×10^4
4	-0.13019164×10^5
5	0.33414230×10^5
6	-0.58711743×10^5
7	0.71426686×10^5
8	-0.59834012×10^5
9	0.33652741×10^5
10	-0.12027350×10^5
11	0.24348205×10^4
12	-0.20807957×10^3

The optimum values are $\epsilon/k = 386$ K and $\sigma = 0.2957$ nm, and it is these values that have been used in the development of the correlation of the viscosity in the limit of zero density in order to secure internal consistency.

It should be pointed out here that we ascribe no particular physical significance beyond reasonableness to the values of σ and ϵ deduced in this fashion. In terms of the Lennard-Jones (12-6) potential model upon which the analysis of the second viscosity virial coefficient is based, the parameters are the well-depth and the separation at zero potential. This should not be taken to mean that the values have any relationship to the true potential of the nonspherical polar ammonia molecule.
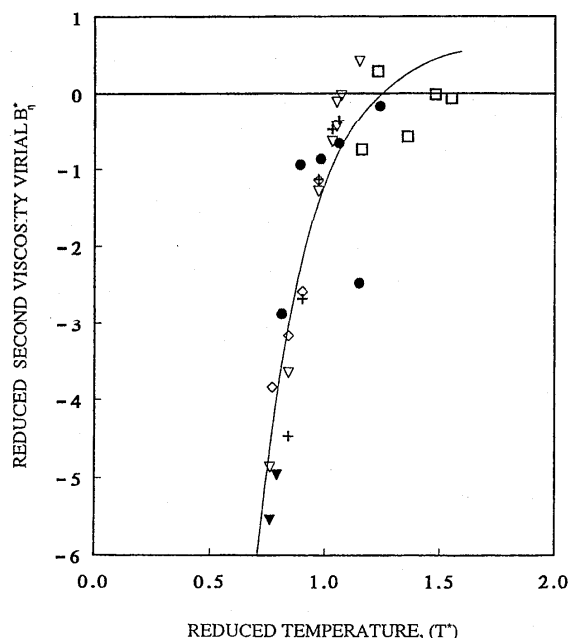

FIG. 3. Comparison of experimental and calculated reduced second viscosity virial coefficients. + Iwasaki and Takahashi;[16] ▼ Iwasaki *et al.*;[11] □ Sun and Storvick;[13] ◇ Hongo and Iwasaki;[10] ▽ Golubev and Likhachev;[14] ● Carmichael *et al.*;[12] ———— Eq. (9).

TABLE 5. Coefficients for the representation of the excess viscosity of ammonia, Eq. (11).

j	d_{2j}	d_{3j}	d_{4j}
0	0	$0.17366936 \times 10^{-2}$	0
1	0	$-0.64250359 \times 10^{-2}$	0
2	$2.19664285 \times 10^{-1}$	0	$1.67668649 \times 10^{-4}$
3	0	0	$-1.49710093 \times 10^{-4}$
4	$-0.83651107 \times 10^{-1}$	0	$0.77012274 \times 10^{-4}$

4.5. Higher Density Coefficients

In order to evaluate the higher density coefficients $[b_i(T), i = 2$ to $n]$ of Eq. (6) and thus develop the representation of the remaining part of the excess viscosity, it is necessary to perform a statistical fit to the available primary experimental data. For this purpose, we calculate the higher density excess viscosity, $\Delta_h \eta$,

$$\Delta_h \eta(\rho,T) = \eta(\rho,T) - \eta_0(T) - b_1(T)\rho = \sum_{i=2}^{n} b_i \rho^i.$$

(10)

Table 2 lists the primary sources used in the determination of $\Delta_h \eta(\rho,T)$. We have consistently employed Eqs. (7)–(9) to evaluate the contribution $b_1(T)\rho$ in the determination. Whenever possible the values of $\eta_0(T)$ reported by each investigator have been employed so as to reduce the effects of systematic errors in individual measurements. Where this has not been possible, the correlated values given by Eqs. (3) to (5) have been used.

The coefficients $[b_i(T), i = 2$ to $n]$ have been assumed to be of the form

$$b_i = \sum_{j=0}^{m} d_{ij}/T^{*j},$$

(11)

where T^* is defined by Eq. (5), and the coefficients d_{ij}, as well as the optimum values of n and m, were determined by the application of the SEEQ technique.[54] In this process each datum was given a weight dependent on the estimated uncertainty. The resulting coefficients are given in Table 5.

5. Results and Discussion

The extent of the agreement between the representative equations developed in this work and the experimental viscosity data is briefly reviewed below. Viscosity values of ammonia calculated by the correlation are compared with experimental data in order to assess the performance of the correlation. The deviations of the experimental data of Iwasaki and Takahashi[16] along six isotherms from the present correlation are illustrated in Fig. 4. The deviations of the data of Hongo and Iwasaki[10] along four isotherms from the correlation are shown in Fig. 5. The deviations of the experimental data of Iwasaki *et al.*[11] along two isotherms from the calculated values are shown in Fig. 6. Comparison of the measurements of Iwasaki and Takahashi[16] with the later measurements of Hongo and Iwasaki,[10] using a similar type of oscillating disc instrument but with additional refine-
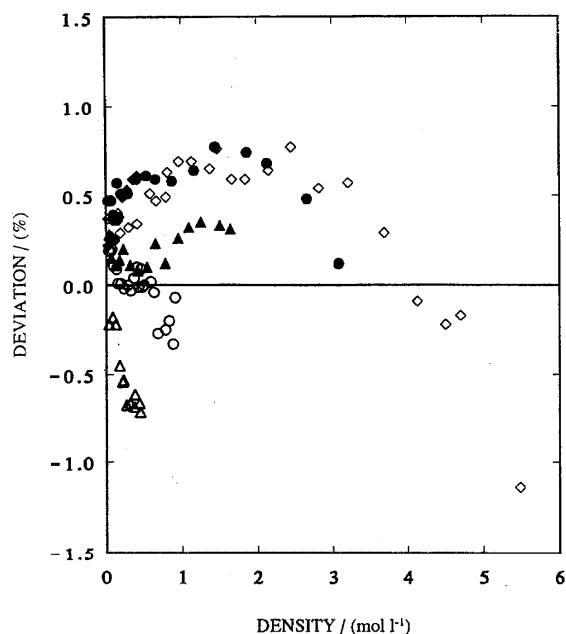
FIG. 4. Deviations of data of Iwasaki and Takahashi[16] from the correlation. The deviations are defined as: $100(\mu_{exp}-\mu_{cal})/\mu_{exp}$. △ 298.14 K isotherm; ○ 323.13 K isotherm; ▲ 348.12 K isotherm; ● 373.12 K isotherm; ◇ 398.13 K isotherm; ◆ 408.13 K isotherm.

FIG. 6. Deviations of data of Iwasaki et al.[11] from the correlation. The deviations are defined as: $100(\mu_{exp}-\mu_{cal})/\mu_{exp}$. △ 293.14 K isotherm; ○ 303.13 K isotherm.

ments to improve accuracy reveals a small but systematic difference between the two sets at elevated temperatures. The data sources agree well at 298.14 and 323.14 K but differ by up to 0.3% and 0.7% on the 348.12 and 373.12 K isotherms, respectively, as shown by Fig. 7. The two isotherms of Iwasaki et al.[11] (293.14 and 303.13 K) are close to the two

low-temperature isotherms of Hongo and Iwasaki[10] and of Iwasaki and Takahashi[16] and exhibit the same behavior as the latter ones as indicated by Fig. 7. These three sources of data are considered to be the most accurate sets of measurements. They are found to be consistent in the regions of overlap and are represented by the correlation within ±1%.
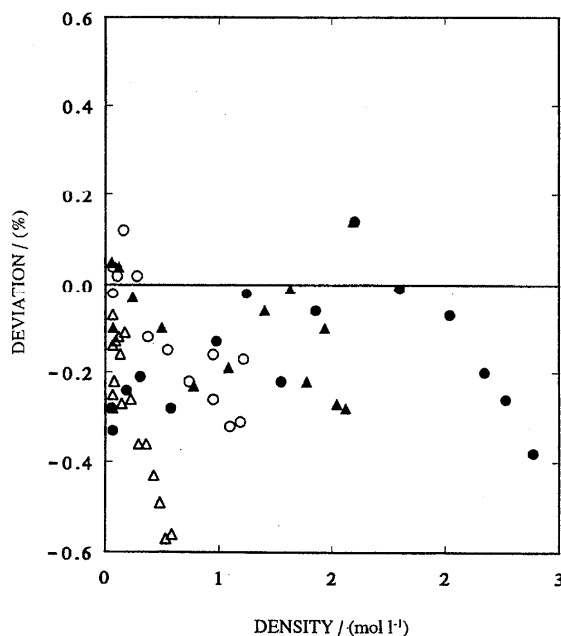
FIG. 5. Deviations of data of Hongo and Iwasaki[10] from the correlation. The deviations are defined as: $100(\mu_{exp}-\mu_{cal})/\mu_{exp}$. △ 298.14 K isotherm; ○ 323.13 K isotherm; ▲ 348.13 K isotherm; ● 373.12 K isotherm.
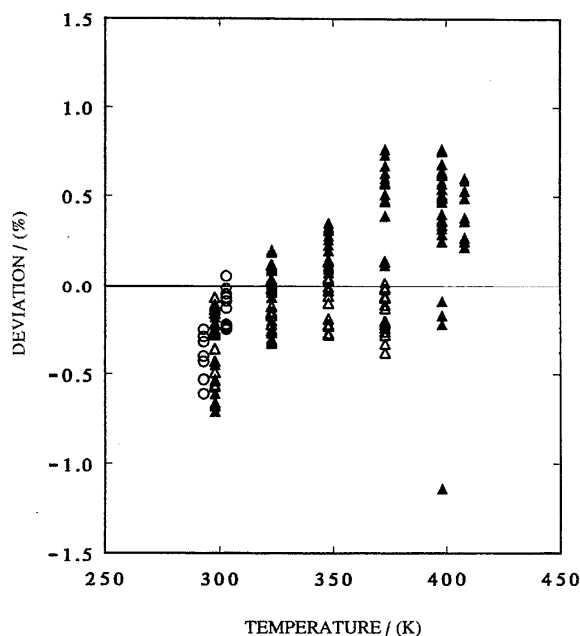
FIG. 7. Deviations of data of Iwasaki and Takahashi[16] ▲; Hongo and Iwasaki[10] △; and Iwasaki et al.[11] ○ from the correlation. The deviations are defined as: $100(\mu_{exp}-\mu_{cal})/\mu_{exp}$.
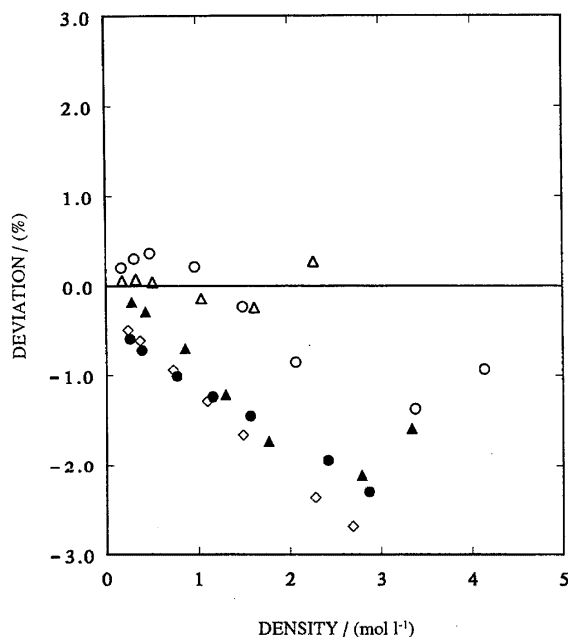
FIG. 8. Deviations of data of Sun and Storvick[13] from the correlation. The deviations are defined as: $100(\mu_{exp}-\mu_{cal})/\mu_{exp}$. △ 448.11 K isotherm; O 473.11 K isotherm; ▲ 523.11 K isotherm; ● 573.11 K isotherm; ◇ 598.11 K isotherm.
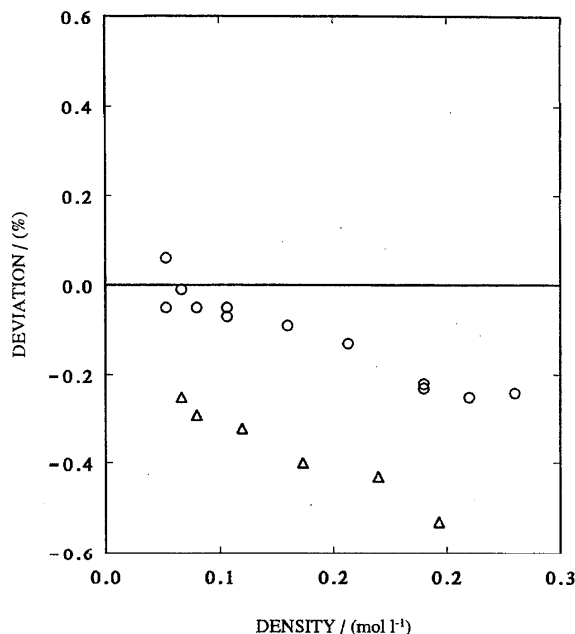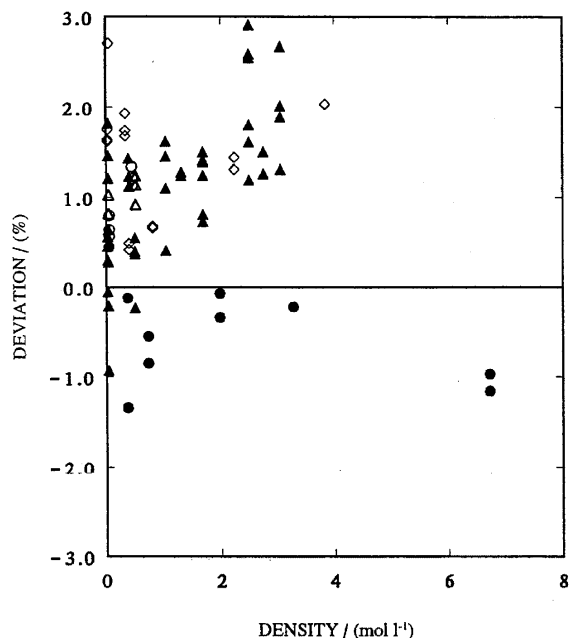

FIG. 9. Deviations of data of Carmichael et al.[12] from the correlation. The deviations are defined as: $100(\mu_{exp}-\mu_{cal})/\mu_{exp}$. △ 310.91 K isotherm; O 344.23 K isotherm; ▲ 377.57 K isotherm; ● 444.25 K isotherm; ◇ 477.60 K isotherm.

Figures 8, 9, and 10 show the deviations of the data of Sun and Storvick,[13] Carmichael et al.,[12] and Golubev and Likhachev[14] from the calculated values. In the overlapping regions, the magnitudes of the deviations of these three sets are consistent as shown by Fig. 11 and fall within the estimated accuracies.

The liquid region has also been found to be well represented by the new correlation. Figure 12 displays the deviations of the experimental liquid viscosity data from the calculated values. Most of the data, either on the saturation boundary or in the subcooled liquid region, are reproduced by the representation within ±2%. The sets of Makhija and Stairs[15] and Carmichael et al.[12] have been reproduced by the correlation within the ascribed uncertainties. As anticipated from the critical assessment of the method of measurement employed by Carmichael et al.,[12] the high temperature data show the largest deviations as illustrated by Fig. 13.

The secondary experimental data have been found to be, in general, represented by the correlation within their estimated uncertainties and with no discernible systematic behavior. The plots containing the deviations of the data examined are included in Appendix I. A selection of secondary gas phase data comprising the 410.91 K isotherm of Carmichael et al.,[12] the data of Trautz and Heberling[20] below 800 K and the data sets of Pal and Bhattacharyya,[55] Chakraborti and Gray,[29] Rankine and Smith,[27] Van Cleave and Maass,[28] Edwards and Worswick,[56] Bhattacharyya et al.,[57] Pal and Barua,[58] and Rakshit et al.[59] have been used to test the performance of the representation. Their deviations from the correlation are shown in Fig. A1.1. Most of the data are reproduced within ±2% with no apparent systematic trend.

Another selection of secondary liquid data made up of the 410.91 K isotherm of Carmichael et al.[12] and the data sets of

Krynicki and Hennel,[60] Plank and Hunt,[61] Shatenshtein et al.,[62] Wakao and Nagashima,[31] and Fredenhagen[63] have also been employed to test the performance of the correlation. Their deviations are illustrated in Figs. A1.2 and A1.3. They are represented within ±4% with no obvious system-
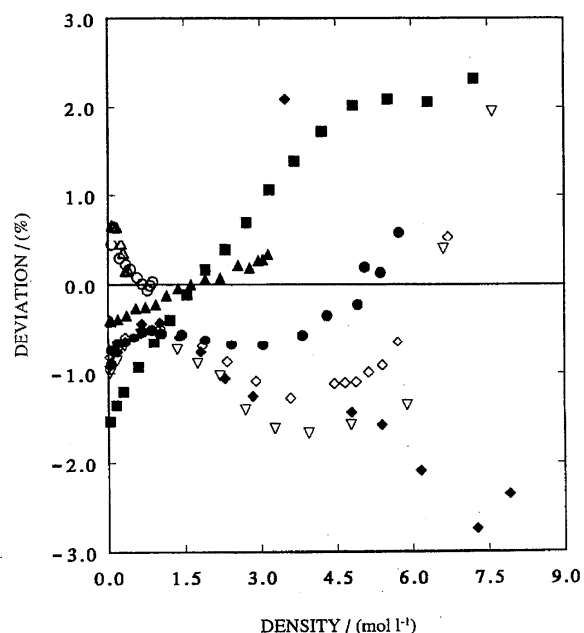
FIG. 10. Deviations of data of Golubev and Likhachev[14] from the correlation. The deviations are defined as: $100(\mu_{exp}-\mu_{cal})/\mu_{exp}$. △ 294.54 K isotherm; O 325.24 K isotherm; ▲ 374.72 K isotherm; ● 397.32 K isotherm; ◇ 403.42 K isotherm; ◆ 406.12 K isotherm; ▽ 413.92 K isotherm; ■ 444.31 K isotherm.
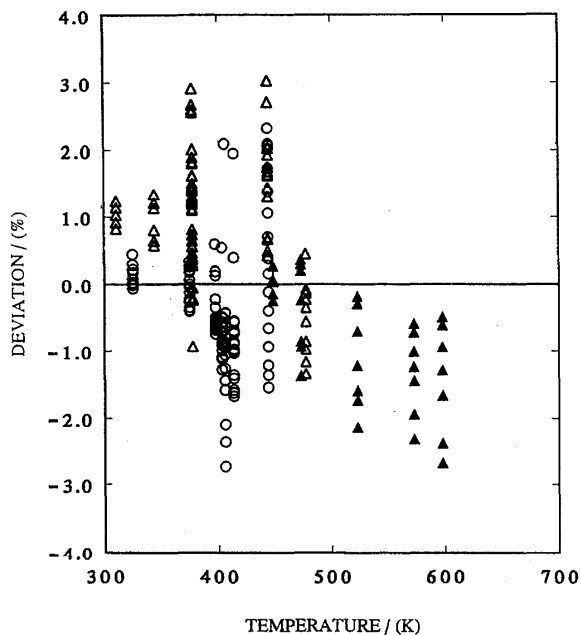
Fig. 11. Deviations of data of Sun and Storvick[13] ▲, Carmichael *et al.*[12] △, and Golubev and Likhachev[14] ○ from the correlation. The deviations are defined as: $100(\mu_{exp} - \mu_{cal})/\mu_{exp}$.

Fig. 13. Deviations of data of Makhija and Stairs[15] ◆; and Carmichael *et al.*[12] △ from the correlation. The deviations are defined as: $100(\mu_{exp} - \mu_{cal})/\mu_{exp}$.

atic deviations. The two sets of Golubev and Petrov[64] and Golubev and Sharapova[65] have been found to have bigger deviations from the calculated values of the representative equations than the rest of the data. The reported data deviate occasionally by as much as 11% from the recommended correlation.

The results of the overall representative equations are summarized in Table 6 which lists the average, the mean and

the root mean square percentage deviation for each source from the correlation as well as the number of data points exceeding the evaluated uncertainty. Several data sets[9,66-74] not included in Table 6 were found to have high deviations from the present correlation. For instance, the data of Carmichael and Sage[72] differ widely from the later data of Carmichael *et al.*[12] The data of Shimotake and Thodos[73] are also in disagreement with the primary set in their region of overlap. Groenier and Thodos[1] based to a large extent their high pressure correlation of the viscosity of ammonia on the data of Carmichael and Sage.[72] For this reason, this correlation is not reliable. The available correlations of ammonia suffer to some extent from inclusion of unreliable data.

6. Tabulations

Tabulations of the viscosity of ammonia are presented in Appendices II and III over the entire range of the correlation, including the saturation line. These tabulations have been generated directly from the representative equations as functions of pressure and temperature using the equation of state of Tillner-Roth *et al.*[5] The tables provide useful reference values as well as assistance in the validation of computer codes during the programming of the representative equations.

On the basis of comparison with experimental secondary data, we can give guidelines regarding the extrapolation of the present correlation outside the validity region. The correlation can be extrapolated up to about 950 K and 0.1 MPa. In this case, the uncertainty surrounding the predicted values is about ±5%. The values above about 723 K, the tempera-

DENSITY / (mol l⁻¹)
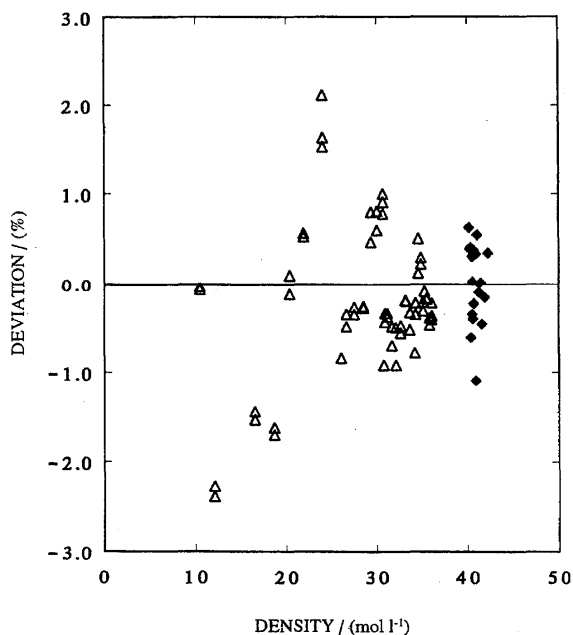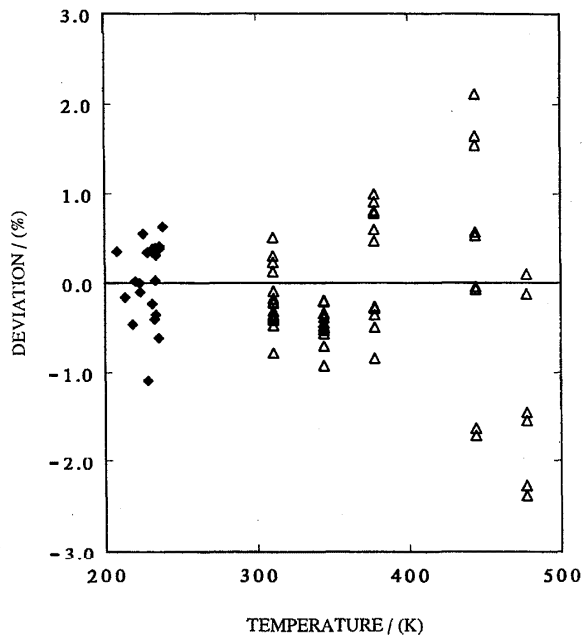
Fig. 12. Deviations of data of Makhija and Stairs[15] ◆; and Carmichael *et al.*[12] △ from the correlation. The deviations are defined as: $100(\mu_{exp} - \mu_{cal})/\mu_{exp}$.

TABLE 6. Summary of results for the analyzed data set.

Primary data Author(s)	Ref.	No of points	Average dev. %	Mean dev. %	rms dev. %	No. of points> 1 standard
Vogel	19	2	0.4	0.4	0.5	0
Braune and Linke	18	9	−0.2	0.8	1.0	1
Trautz and Heberling	20	4	1.7	1.9	2.1	0
Carmichael et al.	12	140	0.5	0.9	1.0	0
Iwasaki et al.	11	20	−0.2	0.2	0.3	2
Burch and Raw	17	11	0.0	0.2	0.2	0
Iwasaki and Takahashi	16	106	0.2	0.4	0.4	0
Makhija and Stairs	15	20	0.0	0.4	0.4	1
Golubev and Likhachev	14	116	−0.3	0.8	1.0	0
Hongo and Iwasaki	10	62	−0.2	0.2	0.2	0
Sun and Storvick	13	35	−0.8	0.9	1.2	4
Overall results		525	0.03	0.6	0.9	8

Secondary data Author(s)	Ref.	No. of points	Average dev. %	Mean dev. %	rms dev. %	No. of points> 1 standard
Rankine and Smith	27	1	1.1	1.1	1.1	0
Edwards and Worswick	56	3	1.0	1.3	1.9	1
Fredenhagen	63	2	2.7	2.7	2.8	0
Trautz and Heberling	20	24	−0.3	0.5	0.6	0
Monoszon and Pleskov	75	6	2.1	4.1	4.7	0
Van Cleave and Maass	28	9	0.1	1.6	1.8	0
Plank and Hunt	61	3	1.0	1.0	1.4	0
Shatenshtein et al.	62	3	1.9	1.9	1.9	0
Golubev and Petrov	64	122	2.6	4.0	4.9	4
Carmichael et al.	12	37	0.5	1.2	1.5	0
Krynicki and Hennel	60	8	−0.1	0.3	0.3	0
Chakraborti and Gray	29	3	0.5	0.5	0.6	0
Pal and Barua	58	5	0.9	1.0	1.2	0
Pal and Bhattacharyya	55	3	1.6	1.6	1.6	0
Bhattacharyya et al.	57	5	−0.4	0.7	0.8	1
Golubev and Sharapova	65	14	0.6	2.7	3.1	0
Rakshit et al.	59	4	−0.6	0.7	0.9	0
Wakao and Nagashima	31	19	−1.1	1.8	2.0	0
Overall results		260	1.4	2.7	3.7	6

ture at which ammonia starts to decompose, are likely to be affected by the rate of ammonia decomposition which increases with temperature. Between 350 K and 580 K, the correlation can be extrapolated up to a pressure of 80 MPa. The values yielded in this case will have an uncertainty of ±10% by comparison with the data of Golubev and Petrov[64] and Golubev and Sharapova.[65]

7. Conclusion

A critical assessment has been made of the available experimental data for the dynamic viscosity of ammonia. An interpolating equation guided by theoretical considerations has been developed to represent the data and the known phenomenological behavior of the fluid over a wide range of temperatures and pressures. Tables of values of viscosity have been prepared together with an assessment of accuracy. The representative equations reproduce the data within their estimated uncertainties, and will be adequate for engineering purposes.

The comparison of the viscosity values calculated from the present representation and the corresponding experimen-

tal data provides the basis for estimating the accuracy of the representation over the validity range of thermodynamic states. In the temperature range 290–400 K and for pressures below 6 MPa, the accuracy is ±0.5%; in the range 400–500 K and for pressures below 10 MPa, the accuracy is ±1.0%; in the range 500–600 K and for pressures below 10 MPa, the accuracy is ±1.5%; and in the range 600–680 K and for pressures below 15 MPa, the accuracy is ±2%. For the liquid region, in the range 270–400 K and for pressures from the saturation pressure to 40 MPa, the accuracy is about ±2%. In the rest of the validity region, the accuracy is estimated to be ±3 to ±5%. A summary of the above information is presented in the form of a tolerance diagram shown in Fig. 14. However, the present assessment highlights the need for more accurate and extensive data for the entire liquid region, with particular emphasis on the region below 300 K and for the gas phase over a wide range of pressures, particularly for temperatures above 523 K.

Owing to the complete absence of experimental data for ammonia in the critical region, it has not been possible to take account of the expected enhancement in dynamic viscosity. For the majority of practical applications, however,
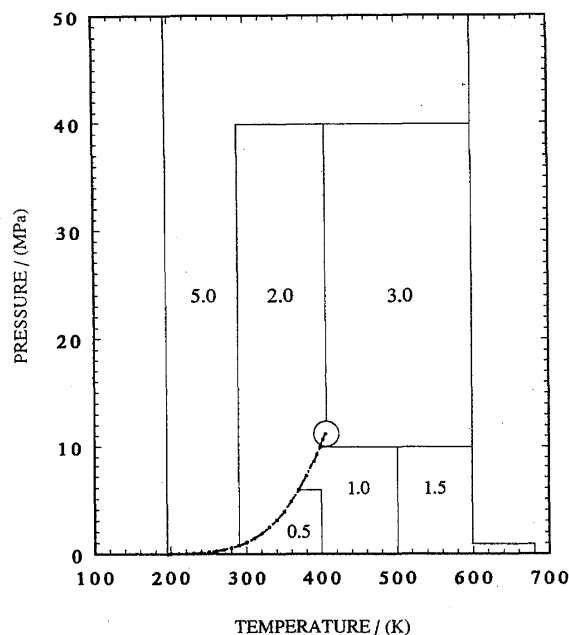
FIG. 14. The extent of the viscosity representation and its estimated uncertainty.

the neglect of the divergence in viscosity in this narrow range of conditions around the critical point should not cause any problems.

8. Acknowledgments

9. References

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10. Appendix I. Deviation Plots of the Selected Secondary Experimental Data from the Correlation (Figs. A1.1–A1.3)

FIG. A1.1. Deviations of a selection of secondary gas-phase viscosity data from the correlation. The deviations are defined as: $100(\mu_{exp} - \mu_{cal})/\mu_{exp}$. $\triangle$ Carmichael et al.;[12] $\bigcirc$ Pal and Bhattacharyya;[55] $\blacktriangle$ Chakraborti and Gray;[29] $\bullet$ Trautz and Heberling;[20] $\diamond$ Rankine and Smith;[27] $\blacklozenge$ Van Cleave and Maass;[28] $\blacksquare$ Edwards and Worswick;[56] $\square$ Bhattacharyya et al.;[57] + Pal and Barua;[58] + Rakshit et al.[59]

FIG. A1.2. Deviations of a selection of secondary liquid viscosity data from the correlation. The deviations are defined as: $100(\mu_{exp} - \mu_{cal})/\mu_{exp}$. $\triangle$ Krynicki and Hennel;[60] $\bigcirc$ Carmichael et al.;[12] $\blacktriangle$ Plank and Hunt;[61] $\bullet$ Shatenshtein et al.;[62] $\diamond$ Wakao and Nagashima;[31] $\blacklozenge$ Fredenhagen.[63]
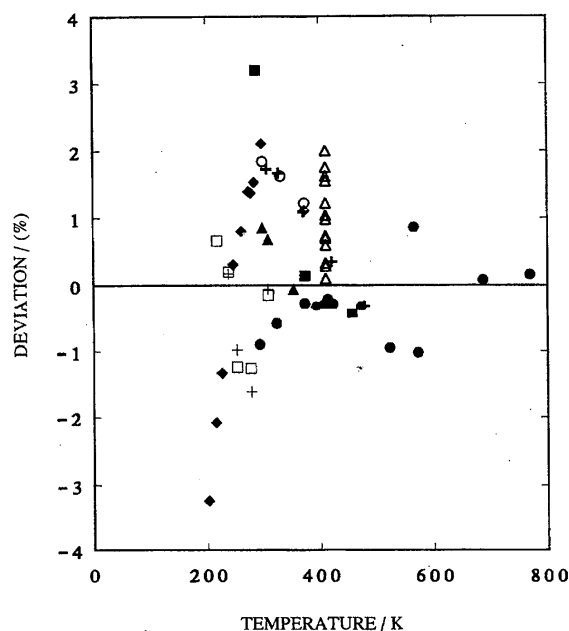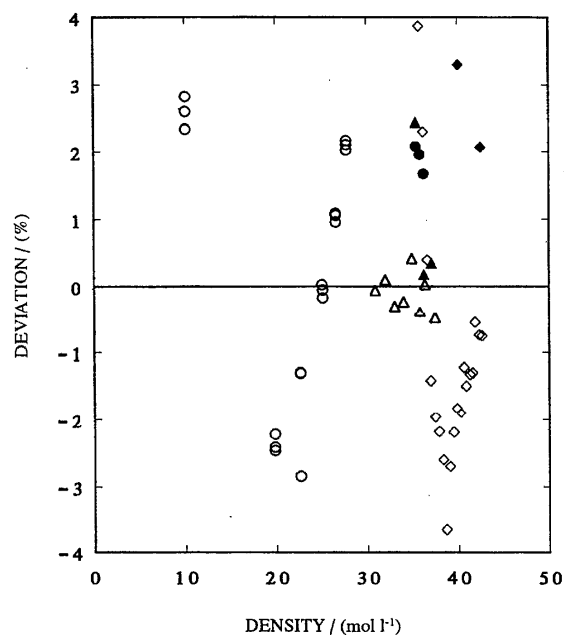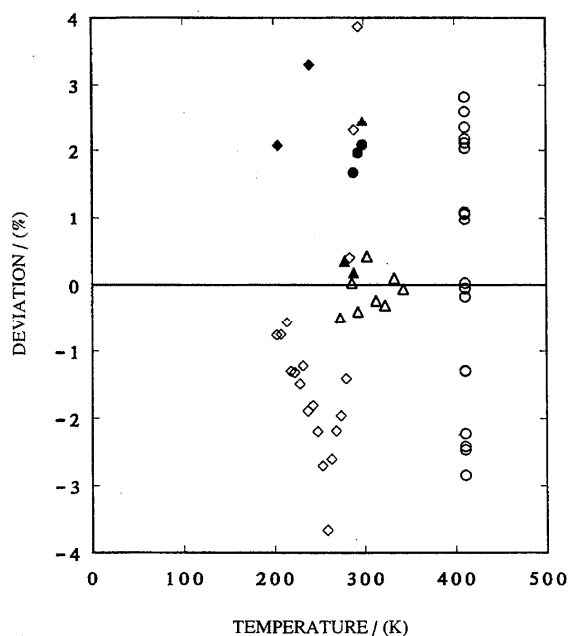

FIG. A1.3. Deviations of a selection of secondary liquid viscosity data from the correlation. The deviations are defined as: $100(\mu_{exp} - \mu_{cal})/\mu_{exp}$. $\triangle$ Krynicki and Hennel;[60] $\bigcirc$ Carmichael et al.;[12] $\blacktriangle$ Plank and Hunt;[61] $\bullet$ Shatenshtein et al.;[62] $\diamond$ Wakao and Nagashima;[31] $\blacklozenge$ Fredenhagen.[63]

11. Appendix II. Tables of Calculated Viscosity Values η (μPa·s)

$T(K)$ $P(MPa)$	200	210	220	230	240	250	260	270	280	290
0.1	507.47	415.13	346.78	295.00	8.06	8.39	8.73	9.08	9.44	9.80
0.5	508.27	415.83	347.40	295.55	255.34	223.45	197.59	176.17	9.29	9.67
1.0	509.28	416.70	348.17	296.23	255.95	224.00	198.10	176.64	158.52	142.93
2.0	511.29	418.46	349.70	297.59	257.17	225.11	199.11	177.58	159.40	143.76
3.0	513.29	420.21	351.24	298.95	258.39	226.21	200.11	178.51	160.27	144.60
4.0	515.30	421.95	352.77	300.30	259.60	227.30	201.12	179.44	161.14	145.42
5.0	517.30	423.70	354.30	301.66	260.81	228.40	202.12	180.36	162.01	146.25
6.0	519.30	425.44	355.83	303.01	262.01	229.49	203.11	181.28	162.87	147.06
7.0	521.30	427.18	357.35	304.36	263.22	230.57	204.10	182.20	163.73	147.88
8.0	523.30	428.92	358.88	305.70	264.42	231.66	205.09	183.11	164.58	148.68
9.0	525.29	430.65	360.40	307.05	265.62	232.74	206.08	184.02	165.43	149.49
10.0	527.29	432.38	361.91	308.39	266.81	233.81	207.06	184.93	166.28	150.28
11.0	529.28	434.11	363.43	309.72	268.01	234.89	208.04	185.83	167.12	151.08
12.0	531.26	435.84	364.94	311.06	269.20	235.96	209.02	186.73	167.96	151.87
13.0	533.25	437.57	366.45	312.39	270.38	237.03	209.99	187.63	168.79	152.66
14.0	535.23	439.29	367.96	313.72	271.57	238.10	210.96	188.52	169.62	153.44
15.0	537.22	441.01	369.46	315.05	272.75	239.16	211.93	189.41	170.45	154.22
16.0	539.20	442.73	370.97	316.37	273.93	240.22	212.89	190.30	171.27	154.99
17.0	541.17	444.45	372.47	317.70	275.11	241.28	213.86	191.18	172.09	155.76
18.0	543.15	446.17	373.97	319.02	276.28	242.34	214.81	192.06	172.91	156.53
19.0	545.12	447.88	375.46	320.34	277.46	243.39	215.77	192.94	173.73	157.29
20.0	547.10	449.59	376.96	321.65	278.63	244.44	216.72	193.81	174.54	158.05
22.5	552.02	453.86	380.68	324.93	281.54	247.06	219.10	195.99	176.55	159.94
25.0	556.93	458.11	384.40	328.20	284.44	249.66	221.46	198.15	178.55	161.80
27.5	561.83	462.36	388.09	331.45	287.33	252.25	223.80	200.29	180.53	163.65
30.0	566.71	466.59	391.78	334.69	290.20	254.82	226.13	202.42	182.49	165.48
32.5	571.59	470.80	395.45	337.92	293.06	257.38	228.44	204.53	184.44	167.29
35.0	576.45	475.01	339.12	341.13	295.91	259.93	230.74	206.63	186.37	169.09
37.5	581.31	479.21	402.77	344.33	298.74	262.46	233.03	208.71	188.29	170.87
40.0	586.15	483.39	406.40	347.52	301.56	264.98	235.30	210.78	190.19	172.64
42.5	590.98	487.56	410.03	350.70	304.38	267.49	237.56	212.84	192.08	174.39
45.0	595.80	491.72	413.65	353.87	307.17	269.99	239.81	214.89	193.96	176.13
47.5	600.61	495.87	417.25	357.02	309.96	272.47	242.05	216.92	195.82	177.85
50.0	605.41	500.01	420.84	360.17	312.74	274.95	244.28	218.94	197.68	179.57

$T(K)$ $P(MPa)$	300	310	320	330	340	350	360	370	380	390
0.1	10.16	10.53	10.90	11.28	11.66	12.04	12.42	12.81	13.19	13.58
0.5	10.05	10.44	10.82	11.21	11.60	11.99	12.38	12.77	13.16	13.56
1.0	9.91	10.32	10.72	11.13	11.53	11.93	12.33	12.73	13.13	13.53
2.0	130.09	117.95	107.01	10.98	11.41	11.83	12.25	12.67	13.08	13.49
3.0	130.90	118.74	107.80	97.79	11.33	11.78	12.22	12.64	13.07	13.49
4.0	131.70	119.53	108.58	98.59	89.53	80.55	12.24	12.68	13.10	13.53
5.0	132.49	120.30	109.35	99.38	90.16	81.45	73.01	12.80	13.21	13.62
6.0	133.27	121.07	110.12	100.16	90.96	82.33	74.01	65.64	13.43	13.80
7.0	134.05	121.83	110.87	100.92	91.75	83.17	74.96	66.82	13.91	14.13
8.0	134.83	122.58	111.62	101.67	92.53	84.00	75.88	67.91	59.62	14.76
9.0	135.60	123.33	112.35	102.41	93.29	84.81	76.77	68.95	60.98	51.81
10.0	136.36	124.07	113.09	103.14	94.04	85.59	77.62	69.93	62.22	53.80
11.0	137.12	124.81	113.81	103.87	94.78	86.36	78.45	70.87	63.36	55.44
12.0	137.88	125.54	114.52	104.58	95.50	87.12	79.26	71.77	64.43	56.88
13.0	138.63	126.26	115.23	105.29	96.22	87.85	80.04	72.63	65.43	58.17
14.0	139.37	126.98	115.94	105.98	96.92	88.58	80.81	73.47	66.39	59.34
15.0	140.11	127.69	116.63	106.67	97.61	89.29	81.56	74.27	67.30	60.43
16.0	140.85	128.40	117.32	107.36	98.30	89.99	82.29	75.06	68.17	61.45
17.0	141.58	129.11	118.01	108.03	98.98	90.68	83.00	75.82	69.00	62.42
18.0	142.31	129.81	118.69	108.70	99.64	91.36	83.70	76.56	69.81	63.33

19.0	143.03	130.50	119.36	109.36	100.30	92.02	84.39	77.28	70.59	64.20
20.0	143.75	131.19	120.03	110.02	100.96	92.68	85.07	77.99	71.35	65.04
22.5	145.54	132.90	121.68	111.63	102.56	94.29	86.70	79.69	73.15	66.99
25.0	147.30	134.58	123.30	113.21	104.12	95.85	88.28	81.31	74.84	68.80
27.5	149.04	136.24	124.90	114.76	105.64	97.36	89.80	82.86	76.44	70.48
30.0	150.76	137.87	126.47	116.29	107.13	98.83	91.28	84.35	77.97	72.07
32.5	152.47	139.49	128.01	117.78	108.59	100.27	92.71	85.79	79.43	73.57
35.0	154.15	141.08	129.54	119.25	110.02	101.68	94.10	87.18	80.84	75.01
37.5	155.82	142.66	131.05	120.70	111.42	103.05	95.46	88.53	82.20	76.38
40.0	157.47	144.22	132.53	122.13	112.80	104.40	96.78	89.85	83.52	77.71
42.5	159.11	145.77	134.00	123.53	114.16	105.72	98.08	91.13	84.79	78.99
45.0	160.74	147.30	135.45	124.92	115.50	107.02	99.35	92.38	86.04	80.23
47.5	162.34	148.81	136.89	126.29	116.82	108.30	100.60	93.61	87.25	81.44
50.0	163.94	150.31	138.30	127.65	118.12	109.56	101.82	94.81	88.43	82.61

$T(K)$										
$P(MPa)$	400	410	420	430	440	450	460	470	480	490
0.1	13.97	14.36	14.75	15.14	15.53	15.92	16.31	16.70	17.09	17.48
0.5	13.95	14.34	14.74	15.13	15.52	15.92	16.31	16.70	17.09	17.48
1.0	13.93	14.33	14.72	15.12	15.52	15.91	16.31	16.70	17.09	17.49
2.0	13.90	14.31	14.71	15.12	15.52	15.92	16.32	16.72	17.12	17.51
3.0	13.90	14.32	14.73	15.14	15.54	15.95	16.35	16.75	17.15	17.55
4.0	13.95	14.36	14.78	15.19	5.59	16.00	16.40	16.81	17.21	17.60
5.0	14.04	14.45	14.86	15.27	15.67	16.08	16.48	16.88	17.28	17.68
6.0	14.19	14.59	14.99	15.39	15.78	16.18	16.58.	16.98	17.37	17.77
7.0	14.45	14.80	15.17	15.55	15.94	16.32	16.71	17.10	17.49	17.88
8.0	14.87	15.12	15.44	15.78	16.14	16.51	16.88	17.26	17.64	18.02
9.0	15.59	15.61	15.81	16.09	16.40	16.74	17.09	17.44	17.81	18.18
10.0	17.23	16.38	16.34	16.50	16.74	17.03	17.34	17.67	18.01	18.37
11.0	45.22	17.79	17.12	17.05	17.17	17.38	17.65	17.94	18.25	18.58
12.0	48.10	22.23	18.35	17.81	17.73	17.83	18.02	18.26	18.53	18.83
13.0	50.19	38.06	20.58	18.89	18.46	18.38	18.46	18.63	18.86	19.12
14.0	51.89	42.56	25.69	20.50	19.41	19.06	19.00	19.08	19.23	19.45
15.0	53.36	45.26	33.05	23.04	20.69	19.92	19.64	19.59	19.67	19.82
16.0	54.67	47.30	37.85	26.86	22.43	20.99	20.41	20.19	20.16	20.24
17.0	55.86	48.98	40.95	31.15	24.73	22.32	21.33	20.89	20.72	20.70
18.0	56.95	50.43	43.25	34.81	27.52	23.96	22.42	21.69	21.35	21.23
19.0	57.98	51.72	45.10	37.68	30.44	25.89	23.69	22.62	22.07	21.81
20.0	58.94	52.89	46.67	39.97	33.15	28.02	25.15	23.66	22.87	22.45
22.5	61.13	55.46	49.87	44.21	38.49	33.24	29.28	26.75	25.23	24.33
25.0	63.10	57.67	52.44	47.32	42.29	37.50	33.35	30.18	27.99	26.55
27.5	64.90	59.64	54.64	49.85	45.23	40.84	36.84	33.48	30.88	28.99
30.0	66.57	61.42	56.58	52.01	47.66	43.55	39.76	36.41	33.62	31.44
32.5	68.14	63.08	58.35	53.92	49.75	45.84	42.22	38.95	36.12	33.78
35.0	69.62	64.62	59.98	55.65	51.61	47.84	44.35	41.17	38.36	35.95
37.5	71.03	66.08	61.49	57.24	53.29	49.62	46.23	43.14	40.36	37.92
40.0	72.37	67.46	62.91	58.72	54.83	51.24	47.93	44.90	42.16	39.72
42.5	73.67	68.77	64.26	60.10	56.27	52.73	49.47	46.49	43.79	41.37
45.0	74.92	70.04	65.55	61.42	57.62	54.12	50.90	47.96	45.29	42.88
47.5	76.15	71.25	66.78	62.67	58.89	55.42	52.24	49.33	46.68	44.28
50.0	77.29	72.42	67.96	63.86	60.10	56.65	53.49	50.60	47.97	45.59

$T(K)$										
$P(MPa)$	500	510	520	530	540	550	560	570	580	590
0.1	17.86	18.25	18.64	19.02	19.40	19.79	20.17	20.55	20.93	21.30
0.5	17.87	18.26	18.64	19.03	19.41	19.80	20.18	20.56	20.94	21.32
1.0	17.88	18.27	18.65	19.04	19.43	19.81	20.20	20.58	20.96	21.34
2.0	17.90	18.30	18.69	19.08	19.46	19.85	20.24	20.62	21.00	21.38
3.0	17.95	18.34	18.73	19.12	19.51	19.90	20.29	20.67	21.05	21.43
4.0	18.00	18.40	18.79	19.18	19.57	19.96	20.34	20.73	21.11	21.49
5.0	18.07	18.47	18.86	19.25	19.64	20.03	20.41	20.80	21.18	21.56
6.0	18.16	18.55	18.95	19.33	19.72	20.11	20.49	20.88	21.26	21.64
7.0	18.27	18.66	19.05	19.43	19.82	20.20	20.58	20.96	21.34	21.72

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8.0	18.40	18.78	19.16	19.54	19.92	20.30	20.68	21.06	21.44	21.81
9.0	18.55	18.92	19.30	19.67	20.05	20.42	20.79	21.17	21.54	21.91
10.0	18.72	19.08	19.45	19.81	20.18	20.55	20.92	21.29	21.66	22.02
11.0	18.92	19.27	19.62	19.97	20.33	20.69	21.05	21.42	21.78	22.14
12.0	19.15	19.48	19.81	20.15	20.50	20.85	21.20	21.56	21.92	22.27
13.0	19.41	19.71	20.03	20.35	20.68	21.02	21.37	21.71	22.06	22.41
14.0	19.70	19.97	20.26	20.57	20.89	21.21	21.54	21.88	22.22	22.56
15.0	20.02	20.26	20.52	20.81	21.10	21.41	21.73	22.05	22.38	22.72
16.0	20.38	20.58	20.81	21.07	21.34	21.63	21.93	22.24	22.56	22.89
17.0	20.79	20.93	21.12	21.35	21.60	21.87	22.15	22.45	22.75	23.06
18.0	21.23	21.32	21.47	21.66	21.88	22.12	22.39	22.66	22.95	23.25
19.0	21.72	21.74	21.84	21.98	22.17	22.39	22.63	22.89	23.17	23.45
20.0	22.26	22.20	22.23	22.34	22.49	22.68	22.90	23.13	23.39	23.66
22.5	23.80	23.50	23.36	23.33	23.37	23.47	23.62	23.80	24.00	24.23
25.0	25.63	25.04	24.68	24.47	24.38	24.38	24.43	24.54	24.68	24.86
27.5	27.66	26.76	26.15	25.75	25.51	25.38	25.34	25.36	25.43	25.54
30.0	29.80	28.60	27.75	27.15	26.74	26.47	26.32	26.25	26.24	26.29
32.5	31.92	30.49	29.41	28.62	28.04	27.64	27.36	27.19	27.10	27.08
35.0	33.95	32.35	31.09	30.13	29.39	28.85	28.46	28.19	28.01	27.91
37.5	35.85	34.13	32.74	31.63	30.76	30.09	29.59	29.21	28.95	28.77
40.0	37.61	35.81	34.32	33.10	32.11	31.33	30.73	30.26	29.91	29.66
42.5	39.24	37.39	35.82	34.52	33.44	32.56	31.86	31.31	30.88	30.56
45.0	40.74	38.87	37.25	35.87	34.72	33.76	32.98	32.35	31.85	31.46
47.5	42.14	40.24	38.59	37.16	35.95	34.93	34.08	33.38	32.82	32.36
50.0	43.44	41.54	39.85	38.39	37.13	36.05	35.15	34.39	33.76	33.25

(T)K P(MPa)	600	610	620	630	640	650	660	670	680
0.1	21.68	22.06	22.43	22.81	23.18	23.55	23.92	24.29	24.66
0.5	21.70	22.07	22.45	22.82	23.20	23.57	23.94	24.31	24.68
1.0	21.72	22.09	22.47	22.84	23.22	23.59	23.96	24.33	24.70
2.0	21.76	22.14	22.52	22.89	23.27	23.64	24.01	24.38	24.75
3.0	21.81	22.19	22.57	22.95	23.32	23.69	24.06	24.44	24.80
4.0	21.87	22.25	22.63	23.01	23.38	23.75	24.12	24.49	24.86
5.0	21.94	22.32	22.70	23.07	23.45	23.82	24.19	24.56	24.93
6.0	22.02	22.39	22.77	23.14	23.52	23.89	24.26	24.63	25.00
7.0	22.10	22.47	22.85	23.22	23.59	23.96	24.33	24.70	25.07
8.0	22.19	22.56	22.93	23.31	23.68	24.04	24.41	24.78	25.15
9.0	22.29	22.66	23.03	23.40	23.76	24.13	24.50	24.86	25.23
10.0	22.39	22.76	23.13	23.49	23.86	24.22	24.59	24.95	25.31
11.0	22.51	22.87	23.23	23.60	23.96	24.32	24.68	25.04	25.40
12.0	22.63	22.99	23.35	23.71	24.07	24.43	24.78	25.14	25.50
13.0	22.76	23.12	23.47	23.83	24.18	24.54	24.89	25.24	25.60
14.0	22.91	23.25	23.60	23.95	24.30	24.65	25.00	25.35	25.70
15.0	23.06	23.39	23.74	24.08	24.43	24.77	25.12	25.46	25.81
16.0	23.21	23.55	23.88	24.22	24.56	24.90	25.24	25.58	25.93
17.0	23.38	23.71	24.03	24.36	24.69	25.03	25.37	25.70	26.04
18.0	23.56	23.87	24.19	24.51	24.84	25.17	25.50	25.83	26.17
19.0	23.75	24.05	24.36	24.67	24.99	25.31	25.64	25.96	26.29
20.0	23.94	24.23	24.53	24.84	25.15	25.46	25.78	26.10	26.42
22.5	24.47	24.73	25.00	25.28	25.56	25.86	26.16	26.46	26.77
25.0	25.05	25.27	25.51	25.76	26.02	26.29	26.56	26.85	27.14
27.5	25.69	25.86	26.06	26.28	26.51	26.75	27.00	27.27	27.54
30.0	26.38	26.50	26.65	26.83	27.03	27.24	27.47	27.71	27.96
32.5	27.11	27.18	27.28	27.42	27.58	27.76	27.96	28.17	28.40
35.0	27.87	27.89	27.94	28.03	28.15	28.30	28.47	28.65	28.86
37.5	28.67	28.62	28.63	28.67	28.76	28.87	29.00	29.16	29.33
40.0	29.49	29.38	29.34	29.34	29.37	29.45	29.55	29.68	29.82
42.5	30.32	30.16	30.06	30.01	30.01	30.04	30.11	30.21	30.33
45.0	31.16	30.95	30.79	30.70	30.66	30.65	30.69	30.75	30.84
47.5	32.01	31.73	31.53	31.40	31.31	31.27	31.27	31.30	31.37
50.0	32.84	32.52	32.28	32.09	31.97	31.89	31.86	31.86	31.90

12. Appendix III. Viscosity of Ammonia Along the Saturation Boundary

T (K)	P (MPa)	$\rho_{vap.}$ (mol·l^{-1})	$\eta_{vap.}$ (μPa·s)	$\rho_{liq.}$ (mol·l^{-1})	$\eta_{liq.}$ (μPa·s)
196	0.0063	0.0039	6.85	43.0041	553.31
200	0.0087	0.0052	6.95	42.7544	507.28
210	0.0177	0.0102	7.21	42.1111	414.98
220	0.0338	0.0187	7.48	41.4417	346.68
230	0.0604	0.0322	7.77	40.7482	294.95
240	0.1022	0.0527	8.06	40.0318	254.85
250	0.1649	0.0824	8.36	39.2933	223.08
260	0.2553	0.1242	8.66	38.5326	197.34
270	0.3811	0.1813	8.96	37.7485	176.06
280	0.5509	0.2573	9.27	36.9389	158.12
290	0.7744	0.3566	9.58	36.1008	142.74
300	1.0617	0.4845	9.89	35.2298	129.33
310	1.4240	0.6470	10.22	34.3199	117.49
320	1.8728	0.8520	10.56	33.3634	106.91
330	2.4205	1.1094	10.93	32.3495	97.32
340	3.0803	1.4325	11.33	31.2641	88.55
350	3.8660	1.8399	11.79	30.0867	80.43
360	4.7929	2.3598	12.35	28.7879	65.49
370	5.8778	3.0375	13.05	27.3212	65.49
380	7.1403	3.9558	14.02	25.6059	58.31
390	8.6045	5.2979	15.53	23.4655	50.88
394	9.2538	6.0518	16.43	22.3912	47.62
398	9.9436	7.0447	17.67	21.0667	43.95
402	10.6777	8.5479	19.69	19.1642	39.20