The Viscosity of Nitrogen, Oxygen, and Their Binary Mixtures in the Limit of Zero Density

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The paper presents a concise and accurate representation of the viscosity of nitrogen, oxygen, and their binary mixtures at the limit of zero density and in the temperature range 110–2100 K, which can be programed easily on a computer. The correlation is founded upon the semiclassical kinetic theory of polyatomic gases and a body of critically evaluated experimental data. Use is also made of the principle of corresponding states to extend the correlation outside of the temperature range for which direct experimental results exist. The optimum correlation has an associated uncertainty of $\pm$ 0.3% around room temperature, but it rises to a maximum of $\pm$ 2% at either extreme of the temperature range. A secondary representation of the viscosity of the same gases, providing some saving in computational effort and a further extension of the temperature range at the expense of a small loss of accuracy, is also presented. The relationship of this second representation to similar correlations for other gases makes it attractive for some purposes.

Key words: corresponding states; gas mixtures; nitrogen; nitrogen–oxygen mixtures; oxygen; viscosity of gases.

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1. Introduction

The most recent critical reviews and correlations of the transport properties of nitrogen, oxygen, and their binary mixtures were published some ten years ago.[1-3] In the intervening period there have been only a small number of new measurements of the viscosity, thermal conductivity, and diffusion coefficient for these systems. However, in all cases the measurements enjoy a higher level of confidence than the earlier results and, in the particular case of oxygen, extend over a range of temperatures within which no data existed previously. For this reason the present paper considers afresh the viscosity of nitrogen, oxygen, and their binary mixtures at the limit of zero density and over a wide range of temperature. The aim has been to produce a correlation of a critically evaluated set of experimental data which is both accurate and simple to use.

Since the publication of the previous correlations there have been some notable theoretical advances in the treatment of the transport properties of polyatomic gases, although the subject has not yet progressed to the stage characteristic of the monatomic gases.[4] Thus, whereas a formal kinetic theory exists for both monatomic and polyatomic gases, it is only possible to perform exact and routine calculations of the transport properties from an intermolecular pair potential for the former. This is because the anisotropic potentials characteristic of the interactions of polyatomic gases, as well as the existence of internal energy, complicate the molecular collision dynamics to a point where even with the fastest computers the exact evaluation of transport cross sections is not yet possible. The approximations which have been proposed to reduce the computational burden[4,5] therefore remain of unproven validity although their use is widespread.[4-6] In any event, the true nature of the potential describing the interaction of any two polyatomic molecules, with the possible exception of hydrogen,[4] remains obscure. The consequence of all of these facts is that the guidance to be obtained from theory in the development of a correlation scheme for the transport properties of polyatomic gases is considerably more limited than for the monatomic gases, and a correspondingly greater reliance must be placed on direct measurements. It follows that a careful selection of the experimental data upon which to base the present correlation is essential.

2. Experimental Data

It has been recognized for some time that most measurements of the viscosity of gases carried out before 1969 are subject to a considerable systematic error, particularly at high temperatures.[7] The confirmation of this fact rested upon indirect comparisons of the results of molecular beam scattering studies with the viscosity data for monatomic gases. In the case of polyatomic gases there are no such independent sources of information which can be used to judge the value of particular results.[4] Consequently the selection of the most reliable viscosity data to employ in a correlation must rest entirely upon an assessment of the measurement technique employed and the precision attained. To assist in this assessment it is convenient to define two categories of experimental data.

(i) Primary Data

These are the results of measurements carried out with an instrument of high precision for which a complete working equation and a detailed knowledge of all corrections are available. It is regarded as essential that there should have been some demonstration that the reproducibility of the measurements is commensurate with the estimated precision, as well as some evidence of validation by the reproducing of known results.

(ii) Secondary Data

These are the results of measurements which are of inferior accuracy to primary data. The inferior accuracy may result from a loss in precision attendant upon operation of a well-characterized instrument at extreme conditions of temperature or from the use of all ill-characterized apparatus for which neither high precision nor a complete working equation can be claimed.

The division of experimental data into these categories is obviously to some extent subjective although, in most cases, there would be little disagreement as to the category to which a particular set of data should be assigned. For each

Table 1. Primary experimental data for the viscosity of nitrogen and oxygen

Reference	Technique	Temperature range (K)	Estimated uncertainty (%)	Relative weight (w')
Nitrogen				
Clarke and Smith [14, 15]	Capillary	110-375	±1.5-±0.5	1.8-1b
Smith et al. [16, 17]	Capillary	290-1550	±0.5-±1.5	16-1.8
Guevara et al. [18]	Capillary	1100-2150	±2.0	1
Kestin et al. [8-13]	Oscillating disk	290-970	±0.2-±0.5	100-16
Flynn et al. [19]	Capillary	190-300	±0.2	100
Oxygen				
Hellemans et al. [21]	Oscillating disk	298-770	±0.2-±0.4	25-31
Kestin et al. [9, 21]	Oscillating disk	293-298	±0.2	25
Smith et al. [23]	Capillary	120-300-1700	±1.5-±0.5-±1.5	1-9-1

system (pure nitrogen, pure oxygen, and mixtures of nitrogen and oxygen) we have carried out a survey of the available data and assigned them to one of the two categories. For the purposes of correlation we have included only the primary data, attaching a significance to each datum determined by our estimate of the uncertainty. The secondary data are retained only for comparison purposes. The following sections detail the selected data for each system, together with their estimated uncertainty, a summary of which is included in Table 1. The statistical treatment of the data is described in Sec. 3.

2.1. Nitrogen

The most accurate measurements of the viscosity of nitrogen in the limit of zero density have been performed with the oscillating disk viscometer at Brown University.[8-13] The measurements have been carried out with two different instruments of this type and the reproducibility of the instrument confirmed by independent measurements over a number of years. The measurements extend over the temperature range 290–970 K and have an accuracy that is estimated to be ± 0.2% near ambient temperatures, deteriorating to ± 0.5% at the highest temperatures. Because a complete working equation has been employed for the evaluation of these data, they evidently must be classified as primary data.

The remaining primary data for nitrogen have been obtained with capillary viscometers; most often these instruments are used to perform relative measurements. Generally, the results are of inferior precision and accuracy to those from the oscillating disk instrument, but the results of Smith and his collaborators,[14-17] Guevara and his co-workers,[18] and Ross and his group[19] enjoy a high level of confidence. These results are especially valuable because they extend to lower and higher temperatures than those available to the oscillating disk instruments.

For the work of Smith and his group[14-17] it is estimated that the uncertainty in the experimental data is one of ± 1.5% at the extreme temperatures, which is consistent with the estimates of the authors themselves, but is nearer to ± 0.5% near room temperature. In the case of the measurements which extend below room temperature of Ross and his co-workers,[19] it is estimated that the uncertainty is one of ± 0.2% in accord with that claimed for the data. However, for the work of Guevara et al.[18] we have assigned an estimated uncertainty of ± 2% to the data, which exceeds that claimed by the authors. It is felt that at temperatures in excess of 1500 K the difficulty of temperature measurement may contribute significantly to the uncertainty in the reported viscosity.

It is worthwhile pointing out that the set of results obtained by Johnston and McCloskey[20] which extend to low temperatures have not been included in the class of primary data for nitrogen. This is because, although the measurements are of high precision, the data were evaluated with an incomplete working equation for the oscillating disk viscometer they employed, and insufficient information is available to permit a reevaluation.

2.2. Oxygen

The hazards of work with pure oxygen mean that there are fewer data available for this gas, although new measurements in the last few years have improved the situation. In fact, it is possible to discern four sets of primary data, three emanating from Brown University's oscillating disk viscometers[9,21,22] of which the most recent[22] extends over a reasonable temperature range, from 298–770 K. The data of Smith and his collaborators[23] obtained with a capillary viscometer cover the temperature range 110–1700 K and have an estimated accuracy ranging from ± 0.5% near room temperature to ± 1.5% at the extremes of the temperature range.

There are three other sets of data which have been considered for inclusion in the primary category for oxygen. The first, obtained by Johnston and McCloskey,[20] have been excluded for the same reason as pertained to the same authors' results for nitrogen. The second set of measurements, reported by Clifford et al.,[24] was carried out with a capillary viscometer similar to that employed by Smith and his collaborators, but there are significant systematic differences between the results obtained with the two instruments for oxygen. In view of the proven reliability of the instrument employed by Smith and his group we have chosen to include only this set in the primary set. Finally, Haynes[25] has reported a series of measurements at low temperatures in dense and dilute oxygen which were performed with an oscillating quartz-crystal viscometer. Because this instrument lacks a complete working equation and is inherently less accurate at low densities, the results are excluded from the primary classification.

The remaining data available for oxygen at temperatures above 770 K were determined by Raw and Ellis[26] and Trautz and Zink.[27] Previous work has demonstrated that for other gases their results are in substantial systematic error[1] so that they cannot be included in the analysis.

2.3. Nitrogen–Oxygen Mixtures

There have been just three sets of measurements of the viscosity of nitrogen–oxygen mixtures[22,28,29] of which only two[22,28] are of high accuracy. The measurements by Hellemans et al,[22] made with an oscillating disk viscometer, extend over the temperature range 298–770 K and their results have therefore been adopted as primary data for the development of a correlation.

3. Methodology

The viscosity of a pure gas, in the limit of zero density may always be written in the form[4]

$$\eta = \frac{5}{16}\left(\frac{mkT}{\pi}\right)^{1/2}\frac{1}{\sigma^2\Omega_\eta^*(T^*)}, \qquad (1)$$

in which m is the molecular mass, T the absolute temperature, and k is Boltzmann's constant. The symbol σ represents a length scaling parameter, and Ω_η^* is a functional of the pair potential for the interaction between the molecules of the gas. In the case of spherically symmetric pair potentials between structureless particles, where the potential may

be expressed in a universal reduced form,

$$U^*(r^*) = \frac{U(r/\sigma)}{\epsilon},$$ (2)

it can readily be shown[4] that the functional Ω_η^* is a function only of the reduced temperature $T^* = kT/\epsilon$ and that it is universal among the same interactions. Thus a two-parameter law of corresponding states exists for the viscosity of these gases which is characterized by the values of the scaling parameters σ and ϵ for each interaction. This result has been used to good effect by Kestin and his collaborators[4,30–32] in their treatment of the low density properties of the noble gases. However, it has been necessary to admit that the intermolecular pair potentials among these species are not exactly conformal in the sense prescribed by Eq. (2).[4,32]

For polyatomic gases interacting through nonspherically symmetric pair potentials, $\Omega_\eta^*(T^*)$ depends not only upon the intermolecular pair potential but also upon the internal energy states of the molecules.[4] An exact two-parameter law of corresponding states for the viscosity of such gases cannot, therefore, exist. Nevertheless, there is a considerable body of heuristic evidence to support the validity of an approximate and useful scheme based on the same ideas.[4] Bearing in mind the advantages that accompany the use of a corresponding states procedure for the purposes of extending data for particular systems beyond the temperature range for which direct measurements are available, it seems worthwhile to consider the use of such a procedure for the present systems. This view is reinforced by the structural and chemical similarity of the molecules nitrogen and oxygen to be considered here.

3.1. Nitrogen

The experimental data for nitrogen are by far the most extensive and accurate of the three systems in the present

Table 2. The scaling parameters for the optimum correlation

(a) The energy scaling parameter ϵ_{ij}/k (K):

	N_2	O_2
N_2	104.2	111.7
O_2		126.7

(b) The length scaling parameter σ_{ij} (nm):

	N_2	O_2
N_2	0.3632	0.3511
O_2		0.3385

study so that they are adopted as the basis of the corresponding states correlation. The primary viscosity data for nitrogen have been used to evaluate the functional $\Omega_\eta^*(T^*)$ over the temperature range 110–2100 K. For this purpose we have adopted arbitrary reference values of the scaling parameters ϵ and σ for nitrogen. For convenience we have selected the values deduced by Kestin et al.[4] for their corresponding states correlation, and the values are listed in Table 2. The experimental values of (Ω_η^*, T^*) have subsequently been fitted to an equation of the form

$$\ln \Omega_\eta^* = \sum_{i=0}^{4} a_i (\ln T^*)^i,$$ (3)

which has already proved of value in earlier correlations.[4]

In the fitting procedure, each viscosity datum has been assigned a temperature-dependent statistical weight w_i in the summation of the squares of the deviations which was determined from our estimate of the uncertainty in the viscosity $\Delta\eta$ according to the equation,

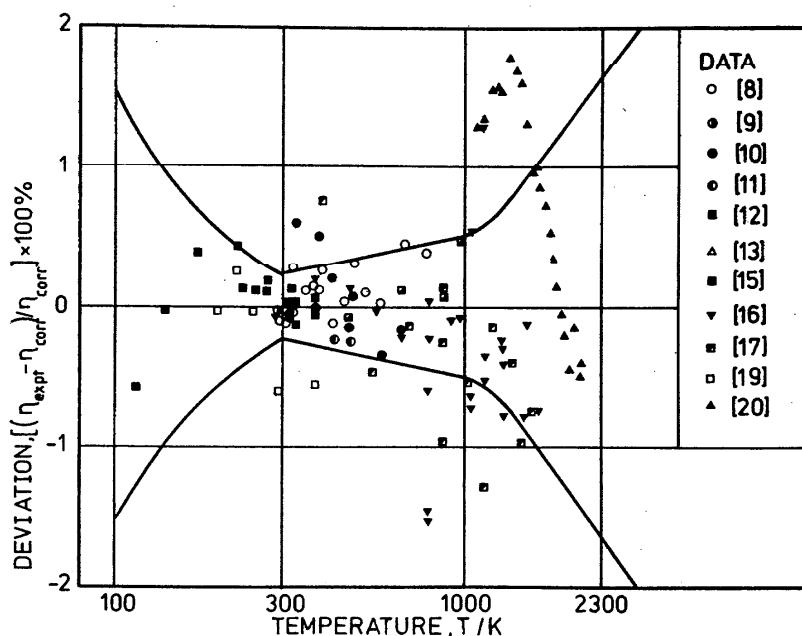$$w_i = (3/\Delta\eta)^2.$$ (4)

FIG. 1. Deviations of the primary data for the viscosity of nitrogen from the correlation.

For a fitting in which the independent variable is $\ln \Omega_\eta^*$, it may be shown that the corresponding weight w_i' is given by

$$w_i' = (3\eta/\Delta\eta)^2. \tag{5}$$

The relative magnitudes of the weights w_i' for the various sets of data are included in Table 1.

The resulting correlation for the viscosity of nitrogen is presented in Sec. 4. Figure 1 contains a plot of the deviations of the primary experimental data from the optimum correlation. The standard deviation is one of $\pm 0.006\,\mu$Pa s whereas the maximum deviation amounts to $\pm 1.6\%$. Generally, the deviations from the correlation are consistent with the estimated uncertainty in the experimental data, although there appear to be systematic differences between the two sets of data available at very high temperatures. The situation is therefore reminiscent of that for the monatomic gases,[32] and it is not possible to reconcile the different sets of results; the difference therefore yields an estimate of the uncertainty in the final correlation.

3.2. Oxygen

The hypothesis that a law of corresponding states may apply to the functionals Ω_η^* for nitrogen and oxygen implies that it should be possible to superimpose the experimental values of $\Omega_\eta^*(T^*)$ for oxygen on the correlation of nitrogen by a suitable choice of the scaling parameters ϵ and σ. The experimental viscosity data for oxygen, weighted in the same manner as for nitrogen, and set out in Table 1, have been fitted to the correlation for nitrogen by means of an optimum selection of σ and ϵ. In a preliminary fitting it was found that inclusion of all of the primary experimental data in this procedure led to a good correspondence at higher temperatures, but increasing departures from correspondence at low temperatures. Because the low temperature departures are sig-

nificant compared with the estimated experimental error, there seems little doubt that they are real and that they arise from differences in the form of the intermolecular pair potentials for nitrogen and oxygen, particularly in the long-range attractive part of the potential.[1,4]

In order to preserve the advantages of the corresponding states treatment we have therefore divided the experimental data for oxygen into two sets, the first set extending upward in temperature from room temperature (290 K) and the second set including data below room temperature. The first set of data has been represented by the correlation of the functional Ω_η^* for nitrogen by means of an optimum choice for the scaling parameters ϵ and σ; the optimum values are listed in Table 2. Figure 2 shows the departures of the primary experimental data from this correlation which are seen to be consistent with the estimated experimental errors. The same figure includes a comparison with the low temperature viscosity data for oxygen which fall further below the corresponding states correlation as the temperature decreases.

The low temperature viscosity data for oxygen have been separately represented by a different correlation based upon Eqs. (1) and (3), using the same parameters ϵ and σ already quoted in Table 2. The overall correlation for the viscosity of oxygen is discussed in Sec. 4.2. It should be noted that the good correspondence between the data for nitrogen and oxygen at high temperatures reinforces the view that the correlation for the former may be used to extend the range of the data for the latter upwards in temperature.

3.3. Nitrogen–Oxygen Mixtures

The kinetic theory of polyatomic gases leads to the following equation for the viscosity of a binary gas mixture[4]:

$$\eta_{\rm mix} = \frac{1 + Z_\eta}{X_\eta + Y_\eta}, \tag{6}$$
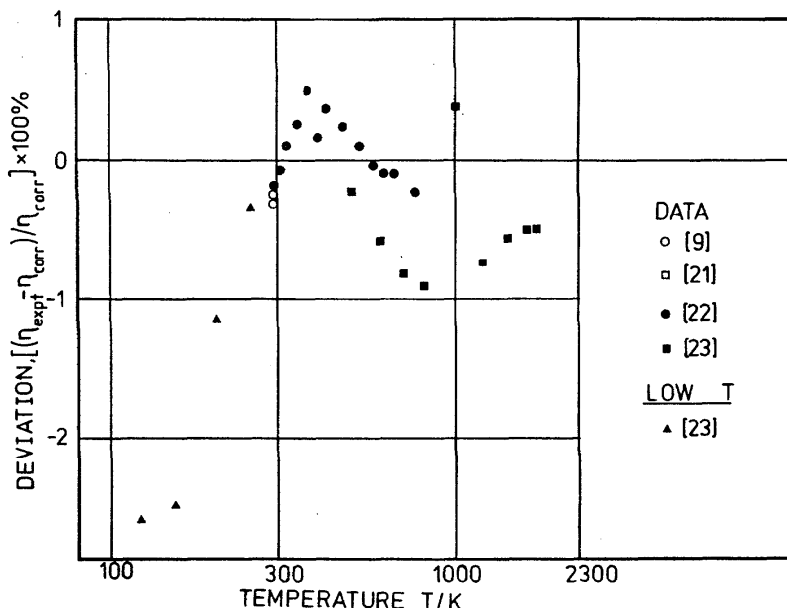

FIG. 2. Deviations of the primary data for the viscosity of oxygen from the corresponding states correlation of Eqs. (1) and (8).

where

$$X_\eta = \frac{x_1^2}{[\eta_1]_1} + \frac{2x_1 x_2}{[\eta_{1\,2}]_1} + \frac{x_2^2}{[\eta_2]_1},$$

$$Y_\eta = \frac{3}{5} A_{12}^* \left\{ \frac{x_1^2}{[\eta_1]_1} \left(\frac{m_1}{m_2}\right) \right.$$

$$+ \frac{2x_1 x_2}{[\eta_{1\,2}]_1} \left[\frac{(m_1 + m_2)^2}{4m_1 m_2} \left(\frac{[\eta_{1\,2}]_1^2}{[\eta_1]_{1+}[\eta_2]_1} \right) \right]$$

$$\left. + \frac{x_2^2}{[\eta_2]_1} \left(\frac{m_2}{m_1}\right) \right\},$$

$$Z_\eta = \frac{3}{5} A_{12}^* \left\{ x_1^2 \left(\frac{m_1}{m_2}\right) + 2x_1 x_2 \right.$$

$$\times \left[\frac{(m_1 + m_2)^2}{4m_1 m_2} \left(\frac{[\eta_{1\,2}]_1}{[\eta_1]_1} + \frac{[\eta_{1\,2}]_1}{[\eta_2]_1} \right) - 1 \right]$$

$$\left. + x_2^2 \left(\frac{m_2}{m_1}\right) \right\},$$

and

$$[\eta_{1\,2}]_1 = \frac{5}{16} \left(\frac{2m_1 m_2 kT}{(m_1 + m_2)\pi} \right)^{1/2} \frac{1}{\sigma_{12}^2 \, \Omega_{\eta_{1\,2}}^* (T_{12}^*)}. \quad (7)$$

Here, the subscripts 1 and 2 denote the different pure components, and x, their mole fractions in the mixture. In addition, A_{12}^* and $\Omega_{\eta_{1\,2}}^*$ are functionals of the pair potential describing the interaction of species 1 and 2. Equation (6) is in fact a first-order approximation to the viscosity of the mixture. However, it has previously been demonstrated that provided the experimental values of the pure gas viscosities are employed to replace the first-order approximations to them $[\eta_i]_1$, no significant error results, especially for mixtures in which the species mass ratio is near unity.[33]

Experimental viscosity data for the binary mixtures of nitrogen and oxygen have been employed to evaluate the functional $\Omega_{\eta_{1\,2}}^*$ at each temperature. For this purpose the value of A_{12}^* has been taken from the correlation given by Kestin et al.[4] Again, invoking the hypothesis of a two-parameter law of corresponding states it should be possible to represent the functional $\Omega_{\eta_{1\,2}}^* (T_{12}^*)$ by means of the correlation for nitrogen together with a suitable choice of the scaling parameters $\sigma_{1\,2}$ and $\epsilon_{1\,2}$. In this case the experimental data extend only over a limited temperature range above room temperature, but, within this region, Fig. 3 demonstrates that a satisfactory description of the data is possible, and the optimum values of the scaling parameters are given in Table 2. Judged by the evidence for pure oxygen, little error should result from the extension of the data to higher temperatures by means of the same correlation. Furthermore, in view of the absence of data at low temperatures, it would seem that the best possible estimate of the viscosity of the mixture below room temperature would be given by the application of the same correlation in this region, provided that an increased uncertainty in the data is allowed. It is this strategy which has been adopted for the correlation of the viscosity of the mixtures by means of Eqs. (6) and (7).

It should be remarked in passing that the values of A_{12}^* employed for the calculations are implicitly based on the correctness of the Mason–Monchick approximation. The
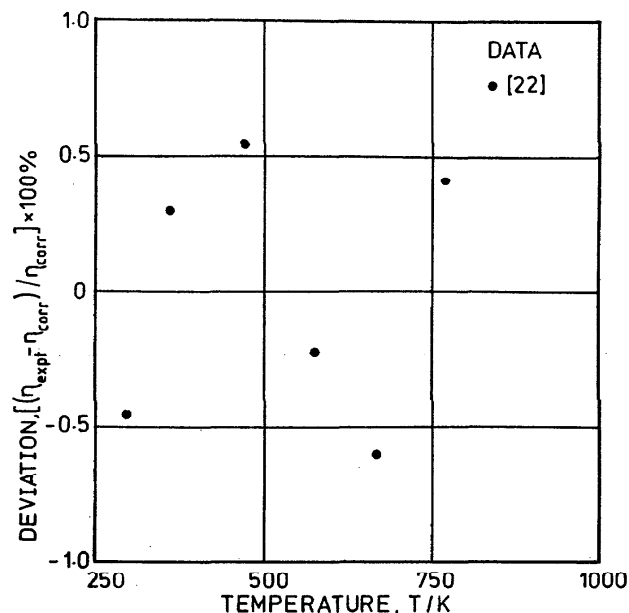
FIG. 3. Deviations of the primary data for the interaction viscosity of nitrogen–oxygen mixtures from the corresponding states correlation of Eqs. (6) and (8).

available evidence[34,35] suggests that, although this may be a reasonable approximation at high temperatures, the estimated uncertainty in the correlation must account for its possible partial failure at low temperatures. In the absence of any direct calculations, this estimate can, of course, be little more than an educated guess.

4. Primary Correlation

4.1. Nitrogen

The viscosity of nitrogen is represented by Eq. (1), together with the correlation for the function $\Omega_\eta^*(T^*)$

$$\ln[\Omega^*(T^*)] = 0.411\,32 - 0.409\,72(\ln T^*) + 0.0228(\ln T^*)^2$$

$$+ 0.0365(\ln T^*)^3 - 0.008\,57(\ln T^*)^4, \quad (8)$$

for

$$1.0 \leqslant T^* \leqslant 20,$$

$$110\ \mathrm{K} \leqslant T \leqslant 2100\ \mathrm{K},$$

as well as the parameters listed in Table 2. The estimates of uncertainty given earlier and the deviation plot contained in Fig. 1 suggest that the uncertainty to be assigned to the correlated viscosity depends upon the temperature range considered. The solid line contained in Fig. 1 delineates the estimated accuracy over the entire temperature range.

Figure 4 contains a comparison of the present correlation for the viscosity of nitrogen with earlier correlations,[1–3] whereas Fig. 5 compares the present correlation with the secondary experimental data not included in its development.[20,27,36–55] The discrepancies between the various correlations reflect the benefit derived from the inclusion of new data in the present treatment and the weight given to different authors' results. So far as the secondary data are con-
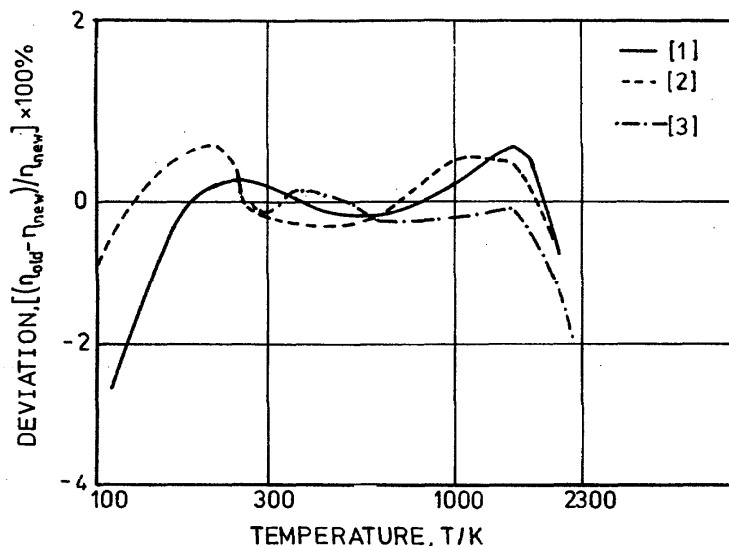
FIG. 4. Deviations of earlier correlations for the viscosity of nitrogen from the present equations.

cerned, it is evident that some results are burdened with large errors. It is noteworthy that the extensive series of measurements carried out by Lavushchev and Lyusternik[52] are in good agreement with the present correlation although the experimental method involved flow through a porous medium and is therefore not characterized by an accurate working equation.

4.2. Oxygen

The viscosity of oxygen is correlated by Eqs. (1) and (8) together with the parameters listed in Table 2 for the tem-

perature range 290–2500 K (reduced temperatures $2.3 \leqslant T^* \leqslant 20$).

At temperatures below 290 K the correlation of the functional Ω_η^* for oxygen is given by the equation

$$\ln[\Omega_\eta^*(T^*)] = 0.440\ 66 - 0.452\ 43(\ln\ T^*)$$

$$+ 0.023\ 75(\ln\ T^*)^2$$

$$+ 0.052\ 36(\ln\ T^*)^3 - 0.0130(\ln\ T^*)^4, \quad (9)$$
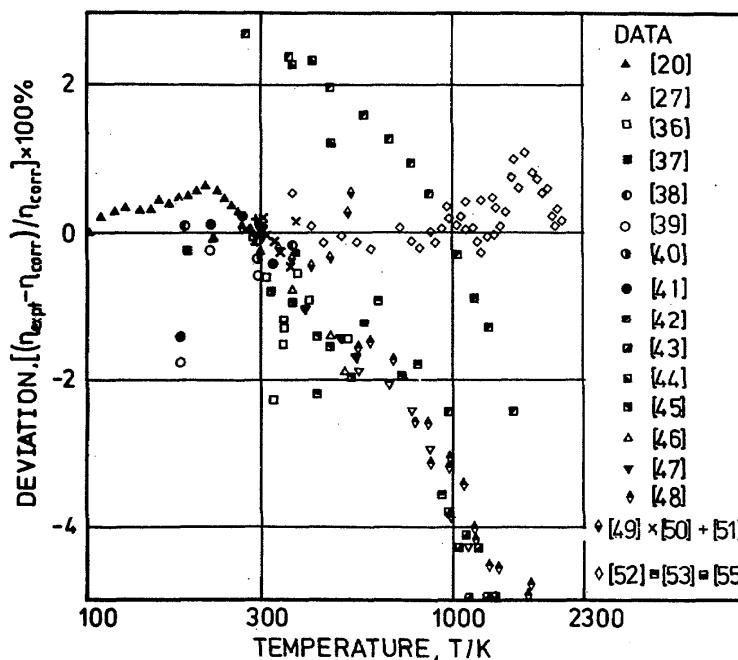
FIG. 5. Comparison of the secondary experimental data for the viscosity of nitrogen with the present correlation.
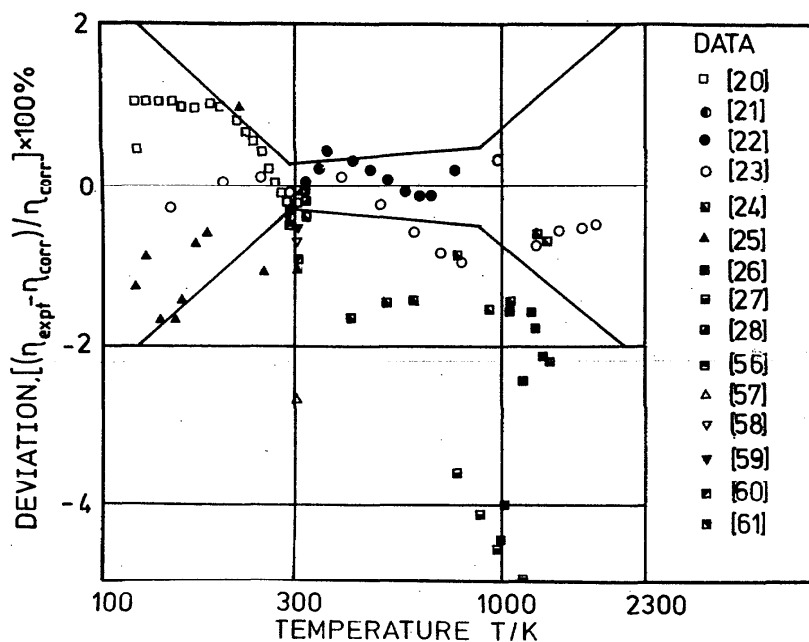
FIG. 6. Deviations of the experimental data for the viscosity of oxygen with the present correlation.

for

$$1.0 < T^* < 2.3,$$

$$110 \text{ K} \leqslant T \leqslant 290 \text{ K},$$

whereas the parameters are still those of Table 2. The values of the viscosity calculated according to Eqs. (8) or (9) have been matched at the joining point, $T = 290$ K. However, no attempt has been made to match exactly the temperature derivatives of the functional Ω^*_η at the same temperature since, in contrast to the situation for monatomic gases,[4] the kinetic theory of polyatomic gases does not endow this derivative with a special significance.

The estimated accuracy of the correlation scheme at temperatures within the range of experimental data is based upon the uncertainty in these data and is indicated in Fig. 6. Outside of this temperature range, the estimated accuracy is based upon that established for nitrogen. Figure 6 also includes a comparison of the correlation with all of the experimental data over the entire temperature range.[21-28,56-61] It is clear that there are quite large differences between the various sets of data for the viscosity of oxygen at low temperatures. However, owing to the use of the data of Smith and his group[23] in its development, the correlation lies close to their data which are considered the most reliable. The maximum
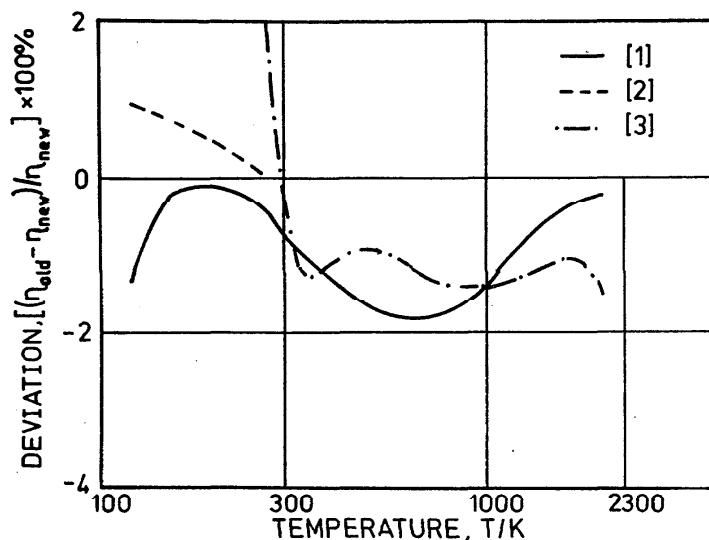
FIG. 7. Comparison of the earlier correlations for the viscosity of oxygen with that of this work.
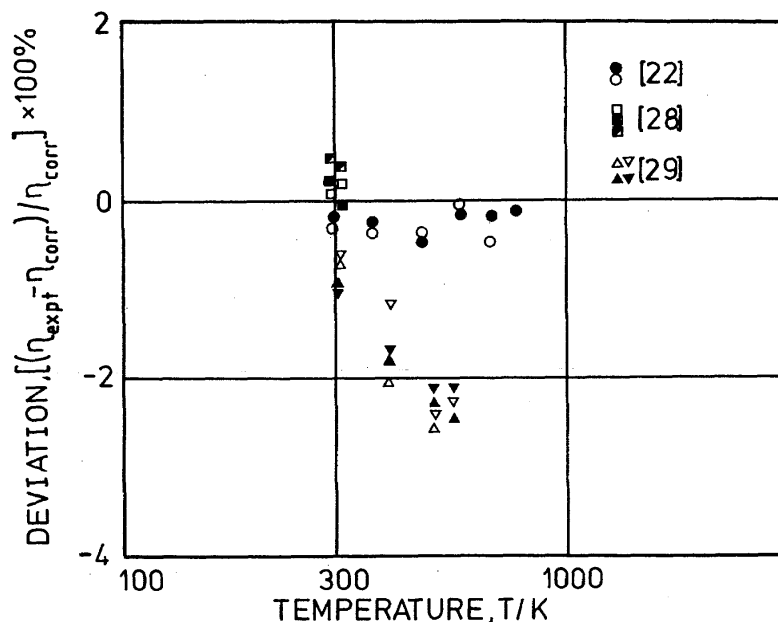
FIG. 8. Deviations of the experimental viscosity data for mixtures of nitrogen and oxygen from the present correlation.

deviation of the primary experimental data from the correlation amounts to only ± 0.9%, whereas the standard deviation is one of ± 0.2 μPa s. Many of the secondary data for oxygen deviate markedly from the correlation confirming that they often have large associated errors. However, the primary data are well represented by the corresponding states correlation at high temperatures, which gives confidence in the extrapolation to temperatures beyond the range of the experimental data.

Figure 7 compares the present correlation for the viscosity of oxygen with those of earlier work.[1-3] The differences are again attributable to the inclusion of new, accurate data, and are somewhat larger than for nitrogen because of the larger quantity of new data.

4.3. Nitrogen–Oxygen Mixtures

The correlation for the viscosity of nitrogen–oxygen mixtures is based upon Eq. (6). The pure gas viscosities are derived from the correlations given in the two preceding sections and the interaction viscosity from Eq. (7) with the correlation of the functional $\Omega_\eta^*(T^*)$ of Eq. (8) and the parameters of Table 2. The quantity A_{12}^* has been obtained from the correlation[4]

$$\ln A_{12}^* = 0.1281 - 0.1108(\ln T^*) + 0.0962(\ln T^*)^2$$

$$- 0.0271(\ln T^*)^3, \tag{10}$$

in which the value of $\epsilon_{1\,2}$ given in Table 2 is to be employed.

Figure 8 contains a plot of the deviations of all of the experimental data[22,28,29] from this correlation. The estimated uncertainty of the correlation is one of ± 0.3% near room temperature rising to ± 3% at extreme temperatures. The standard deviation for the primary data is one of ± 0.06 μPa s and the maximum deviation 0.5%. At low temperatures the estimated uncertainty reflects the uncertainty in the pure gas viscosities, the use of corresponding states to obtain the interaction viscosity, and possible errors in A_{12}^*. The experimental data of Hellemans et al.[22] are well represented by the present correlation, since they were used in its development. The limited, but accurate, results of Iwasaki et al.[28] are also well described by the correlation. However, the results of Trautz and Melster[29] lie systematically below the correlation reflecting the usual systematic error in data from this source.

5. Tabulations

The correlations described in the preceding sections have been employed to generate a table of the viscosity of nitrogen, oxygen, and their binary mixtures over the temperature range 110–2100 K. The data are listed in Table 3. The tabular entries are subject to the uncertainties ascribed to the corresponding correlation, so that Table 3 should be read in conjunction with Figs. 1, 6, and 8.

Table 3. The viscosity of nitrogen, oxygen, and their binary mixtures

Temperature	Viscosity (μPa s)					
T (K)	Mole fraction of nitrogen, χ_{N_2}					
	0.0	0.2	0.4	0.6	0.8	1.0
120.	9.07	8.97	8.84	8.67	8.47	8.24
125.	9.43	9.32	9.18	9.00	8.79	8.54
130.	9.78	9.67	9.52	9.33	9.11	8.85
135.	10.14	10.01	9.85	9.65	9.42	9.15
140.	10.50	10.36	10.18	9.98	9.73	9.45
145.	10.85	10.70	10.52	10.30	10.04	9.75
150.	11.20	11.04	10.84	10.61	10.35	10.05
155.	11.55	11.38	11.17	10.93	10.65	10.34
160.	11.90	11.72	11.49	11.24	10.95	10.63
165.	12.25	12.05	11.82	11.55	11.25	10.92
170.	12.59	12.38	12.14	11.86	11.55	11.21
175.	12.93	12.71	12.45	12.16	11.84	11.49
180.	13.27	13.04	12.77	12.47	12.14	11.77
185.	13.61	13.36	13.08	12.77	12.43	12.05
190.	13.95	13.68	13.39	13.07	12.71	12.33
195.	14.28	14.00	13.70	13.36	13.00	12.60
200.	14.61	14.32	14.00	13.66	13.28	12.88
205.	14.94	14.64	14.31	13.95	13.56	13.15
210.	15.27	14.95	14.61	14.24	13.84	13.42
215.	15.59	15.26	14.91	14.53	14.12	13.68
220.	15.91	15.57	15.21	14.81	14.39	13.94
225.	16.23	15.88	15.50	15.09	14.66	14.21
230.	16.55	16.18	15.79	15.37	14.93	14.47
235.	16.86	16.49	16.08	15.65	15.20	14.72
240.	17.18	16.79	16.37	15.93	15.47	14.98
245.	17.49	17.08	16.66	16.20	15.73	15.23
250.	17.80	17.38	16.94	16.48	15.99	15.48
255.	18.10	17.67	17.22	16.75	16.25	15.73
260.	18.41	17.97	17.50	17.02	16.51	15.98
265.	18.71	18.26	17.78	17.28	16.76	16.23
270.	19.01	18.54	18.05	17.55	17.02	16.47
275.	19.31	18.83	18.33	17.81	17.27	16.71
280.	19.60	19.11	18.60	18.07	17.52	16.95
285.	19.90	19.39	18.87	18.33	17.77	17.19
290.	20.19	19.67	19.14	18.58	18.02	17.43
295.	20.48	19.95	19.40	18.84	18.26	17.66
300.	20.76	20.23	19.67	19.09	18.50	17.90
305.	21.07	20.51	19.94	19.35	18.74	18.13
310.	21.34	20.78	20.19	19.60	18.98	18.36
315.	21.62	21.04	20.45	19.84	19.22	18.59
320.	21.89	21.31	20.71	20.09	19.46	18.81
325.	22.17	21.57	20.96	20.33	19.69	19.04
330.	22.44	21.83	21.21	20.58	19.93	19.26
335.	22.71	22.09	21.46	20.82	20.16	19.49

Table 3. The viscosity of nitrogen, oxygen, and their binary mixtures
--Continued

Temperature	Viscosity, (μPa s)					
T (K)	Mole fraction of nitrogen, X_{N_2}					
	0.0	0.2	0.4	0.6	0.8	1.0
340.	22.98	22.35	21.71	21.06	20.39	19.71
345.	23.24	22.61	21.96	21.29	20.62	19.93
350.	23.51	22.86	22.20	21.53	20.84	20.14
355.	23.77	23.12	22.45	21.76	21.07	20.36
360.	24.03	23.37	22.69	22.00	21.29	20.58
365.	24.29	23.62	22.93	22.23	21.52	20.79
370.	24.55	23.87	23.17	22.46	21.74	21.00
375.	24.81	24.12	23.41	22.69	21.96	21.21
380.	25.07	24.36	23.65	22.92	22.17	21.42
385.	25.32	24.61	23.88	23.14	22.39	21.63
390.	25.57	24.85	24.11	23.37	22.61	21.84
395.	25.82	25.09	24.35	23.59	22.82	22.04
400.	26.07	25.33	24.58	23.81	23.04	22.25
405.	26.32	25.57	24.81	24.03	23.25	22.45
410.	26.57	25.81	25.04	24.25	23.46	22.65
415.	26.82	26.05	25.26	24.47	23.67	22.86
420.	27.06	26.28	25.49	24.69	23.88	23.06
425.	27.30	26.52	25.72	24.90	24.08	23.25
430.	27.54	26.75	25.94	25.12	24.29	23.45
435.	27.79	26.98	26.16	25.33	24.50	23.65
440.	28.02	27.21	26.38	25.55	24.70	23.84
445.	28.26	27.44	26.60	25.76	24.90	24.04
450.	28.50	27.67	26.82	25.97	25.10	24.23
455.	28.74	27.89	27.04	26.18	25.30	24.42
460.	28.97	28.12	27.26	26.38	25.50	24.62
465.	29.20	28.34	27.47	26.59	25.70	24.81
470.	29.43	28.56	27.69	26.80	25.90	25.00
475.	29.67	28.79	27.90	27.00	26.10	25.18
480.	29.90	29.01	28.11	27.20	26.29	25.37
485.	30.12	29.23	28.32	27.41	26.49	25.56
490.	30.35	29.45	28.53	27.61	26.68	25.74
495.	30.58	29.66	28.74	27.81	26.87	25.93
500.	30.80	29.88	28.95	28.01	27.06	26.11
510.	31.25	30.31	29.36	28.41	27.44	26.48
520.	31.69	30.74	29.77	28.80	27.82	26.84
530.	32.13	31.16	30.18	29.19	28.19	27.19
540.	32.57	31.58	30.58	29.57	28.56	27.55
550.	33.00	31.99	30.97	29.95	28.93	27.90
560.	33.43	32.40	31.37	30.33	29.29	28.25
570.	33.85	32.81	31.76	30.71	29.65	28.59
580.	34.27	33.21	32.15	31.08	30.01	28.93
590.	34.69	33.61	32.53	31.45	30.36	29.27
600.	35.10	34.01	32.91	31.81	30.71	29.61
610.	35.51	34.40	33.29	32.18	31.06	29.94
620.	35.92	34.79	33.66	32.54	31.40	30.27

Table 3. The viscosity of nitrogen, oxygen, and their binary mixtures
        --Continued

Temperature   Viscosity (μPa s)

T (K)	Mole fraction of nitrogen, X_{N_2}					
	0.0	0.2	0.4	0.6	0.8	1.0
630.	36.32	35.18	34.04	32.89	31.75	30.60
640.	36.72	35.56	34.41	33.25	32.09	30.93
650.	37.12	35.94	34.77	33.60	32.42	31.25
660.	37.51	36.32	35.13	33.95	32.76	31.57
670.	37.90	36.70	35.50	34.29	33.09	31.89
680.	38.29	37.07	35.85	34.64	33.42	32.21
690.	38.67	37.44	36.21	34.98	33.75	32.52
700.	39.06	37.81	36.56	35.32	34.07	32.83
710.	39.44	38.17	36.91	35.65	34.40	33.14
720.	39.81	38.54	37.26	35.99	34.72	33.45
730.	40.19	38.90	37.61	36.32	35.04	33.76
740.	40.56	39.25	37.95	36.65	35.35	34.06
750.	40.93	39.61	38.29	36.98	35.67	34.36
760.	41.30	39.96	38.63	37.30	35.98	34.66
770.	41.66	40.31	38.97	37.63	36.29	34.96
780.	42.03	40.66	39.30	37.95	36.60	35.26
790.	42.39	41.01	39.64	38.27	36.91	35.55
800.	42.75	41.35	39.97	38.59	37.21	35.85
810.	43.10	41.70	40.30	38.90	37.52	36.14
820.	43.46	42.04	40.62	39.22	37.82	36.43
830.	43.81	42.38	40.95	39.53	38.12	36.72
840.	44.16	42.71	41.27	39.84	38.42	37.00
850.	44.51	43.05	41.60	40.15	38.72	37.29
860.	44.85	43.38	41.92	40.46	39.01	37.57
870.	45.20	43.71	42.24	40.77	39.31	37.85
880.	45.54	44.04	42.55	41.07	39.60	38.14
890.	45.88	44.37	42.87	41.37	39.89	38.42
900.	46.22	44.70	43.18	41.68	40.18	38.69
910.	46.56	45.02	43.49	41.98	40.47	38.97
920.	46.89	45.34	43.80	42.28	40.76	39.25
930.	47.22	45.66	44.11	42.57	41.04	39.52
940.	47.56	45.98	44.42	42.87	41.33	39.80
950.	47.89	46.30	44.73	43.16	41.61	40.07
960.	48.22	46.62	45.03	43.46	41.89	40.34
970.	48.54	46.93	45.34	43.75	42.17	40.61
980.	48.87	47.25	45.64	44.04	42.45	40.88
990.	49.19	47.56	45.94	44.33	42.73	41.15
1000.	49.52	47.87	46.24	44.62	43.01	41.41
1010.	49.84	48.18	46.54	44.91	43.29	41.68
1020.	50.16	48.49	46.84	45.19	43.56	41.94
1030.	50.48	48.80	47.13	45.48	43.84	42.21
1040.	50.80	49.10	47.43	45.76	44.11	42.47
1050.	51.11	49.41	47.72	46.05	44.38	42.73
1060.	51.43	49.71	48.01	46.33	44.65	43.00
1070.	51.74	50.02	48.31	46.61	44.93	43.26

Table 3. The viscosity of nitrogen, oxygen, and their binary mixtures
--Continued

| Temperature | Viscosity (μPa s) | | | | | |

| T (K) | Mole fraction of nitrogen, X_{N_2} | | | | | |
	0.0	0.2	0.4	0.6	0.8	1.0
1080.	52.05	50.32	48.60	46.89	45.20	43.52
1090.	52.36	50.62	48.89	47.17	45.46	43.77
1100.	52.67	50.92	49.17	47.45	45.73	44.03
1110.	52.98	51.22	49.46	47.72	46.00	44.29
1120.	53.29	51.51	49.75	48.00	46.27	44.55
1130.	53.60	51.81	50.03	48.27	46.53	44.80
1140.	53.90	52.10	50.32	48.55	46.80	45.06
1150.	54.21	52.40	50.60	48.82	47.06	45.31
1160.	54.51	52.69	50.89	49.10	47.32	45.56
1170.	54.81	52.98	51.17	49.37	47.58	45.82
1180.	55.11	53.27	51.45	49.64	47.85	46.07
1190.	55.41	53.56	51.73	49.91	48.11	46.32
1200.	55.71	53.85	52.01	50.18	48.37	46.57
1210.	56.01	54.14	52.29	50.45	48.63	46.82
1220.	56.31	54.43	52.57	50.72	48.89	47.07
1230.	56.61	54.72	52.84	50.98	49.14	47.32
1240.	56.90	55.00	53.12	51.25	49.40	47.57
1250.	57.20	55.29	53.39	51.52	49.66	47.82
1260.	57.49	55.57	53.67	51.78	49.91	48.06
1270.	57.78	55.86	53.94	52.05	50.17	48.31
1280.	58.08	56.14	54.22	52.31	50.43	48.56
1290.	58.37	56.42	54.49	52.58	50.68	48.80
1300.	58.66	56.70	54.76	52.84	50.93	49.05
1310.	58.95	56.98	55.03	53.10	51.19	49.29
1320.	59.24	57.26	55.30	53.36	51.44	49.53
1330.	59.52	57.54	55.57	53.63	51.69	49.78
1340.	59.81	57.82	55.84	53.89	51.94	50.02
1350.	60.10	58.10	56.11	54.15	52.20	50.26
1360.	60.39	58.38	56.38	54.41	52.45	50.51
1370.	60.67	58.65	56.65	54.66	52.70	50.75
1380.	60.96	58.93	56.92	54.92	52.95	50.99
1390.	61.24	59.20	57.18	55.18	53.20	51.23
1400.	61.52	59.48	57.45	55.44	53.45	51.47
1410.	61.81	59.75	57.72	55.70	53.70	51.71
1420.	62.09	60.03	57.98	55.95	53.94	51.95
1430.	62.37	60.30	58.25	56.21	54.19	52.19
1440.	62.65	60.57	58.51	56.47	54.44	52.43
1450.	62.93	60.84	58.77	56.72	54.69	52.67
1460.	63.21	61.11	59.04	56.98	54.93	52.91
1470.	63.49	61.39	59.30	57.23	55.18	53.15
1480.	63.77	61.66	59.56	57.48	55.42	53.38
1490.	64.05	61.93	59.82	57.74	55.67	53.62
1500.	64.32	62.20	60.08	57.99	55.92	53.86
1510.	64.60	62.46	60.35	58.24	56.16	54.10
1520.	64.88	62.73	60.61	58.50	56.41	54.33

Table 3. The viscosity of nitrogen, oxygen, and their binary mixtures
--Continued

Temperature   Viscosity (µPa s)

T (K)	Mole fraction of nitrogen, X_{N_2}					
	0.0	0.2	0.4	0.6	0.8	1.0
1530.	65.15	63.00	60.87	58.75	56.65	54.57
1540.	65.43	63.27	61.13	59.00	56.89	54.80
1550.	65.70	63.54	61.39	59.25	57.14	55.04
1560.	65.98	63.80	61.64	59.50	57.38	55.28
1570.	66.25	64.07	61.90	59.76	57.62	55.51
1580.	66.52	64.33	62.16	60.01	57.87	55.75
1590.	66.80	64.60	62.42	60.26	58.11	55.98
1600.	67.07	64.87	62.68	60.51	58.35	56.22
1610.	67.34	65.13	62.93	60.76	58.59	56.45
1620.	67.61	65.39	63.19	61.01	58.84	56.68
1630.	67.88	65.66	63.45	61.25	59.08	56.92
1640.	68.16	65.92	63.70	61.50	59.32	57.15
1650.	68.43	66.19	63.96	61.75	59.56	57.39
1660.	68.70	66.45	64.22	62.00	59.80	57.62
1670.	68.97	66.71	64.47	62.25	60.04	57.85
1680.	69.23	66.97	64.73	62.50	60.28	58.09
1690.	69.50	67.24	64.98	62.74	60.52	58.32
1700.	69.77	67.50	65.24	62.99	60.76	58.55
1710.	70.04	67.76	65.49	63.24	61.00	58.78
1720.	70.31	68.02	65.75	63.49	61.24	59.02
1730.	70.58	68.28	66.00	63.73	61.48	59.25
1740.	70.84	68.54	66.25	63.98	61.72	59.48
1750.	71.11	68.80	66.51	64.23	61.96	59.71
1760.	71.38	69.06	66.76	64.47	62.20	59.95
1770.	71.64	69.32	67.01	64.72	62.44	60.18
1780.	71.91	69.58	67.27	64.96	62.68	60.41
1790.	72.17	69.84	67.52	65.21	62.92	60.64
1800.	72.44	70.10	67.77	65.46	63.16	60.87
1810.	72.70	70.36	68.02	65.70	63.40	61.10
1820.	72.97	70.62	68.27	65.95	63.63	61.34
1830.	73.23	70.87	68.53	66.19	63.87	61.57
1840.	73.50	71.13	68.78	66.44	64.11	61.80
1850.	73.76	71.39	69.03	66.68	64.35	62.03
1860.	74.03	71.65	69.28	66.93	64.59	62.26
1870.	74.29	71.90	69.53	67.17	64.82	62.49
1880.	74.55	72.16	69.78	67.42	65.06	62.72
1890.	74.82	72.42	70.03	67.66	65.30	62.95
1900.	75.08	72.68	70.28	67.90	65.54	63.18
1910.	75.34	72.93	70.53	68.15	65.78	63.41
1920.	75.60	73.19	70.79	68.39	66.01	63.65
1930.	75.87	73.45	71.04	68.64	66.25	63.88
1940.	76.13	73.70	71.29	68.88	66.49	64.11
1950.	76.39	73.96	71.54	69.12	66.73	64.34
1960.	76.65	74.21	71.79	69.37	66.96	64.57
1970.	76.91	74.47	72.04	69.61	67.20	64.80

Table 3. The viscosity of nitrogen, oxygen, and their binary mixtures --Continued

Temperature	Viscosity (µPa s)					
T (K)	Mole fraction of nitrogen, X_{N_2}					
	0.0	0.2	0.4	0.6	0.8	1.0
1980.	77.17	74.72	72.29	69.86	67.44	65.03
1990.	77.43	74.98	72.53	70.10	67.67	65.26
2000.	77.70	75.24	72.78	70.34	67.91	65.49
2010.	77.96	75.49	73.03	70.59	68.15	65.72
2020.	78.22	75.75	73.28	70.83	68.39	65.95
2030.	78.48	76.00	73.53	71.07	68.62	66.18
2040.	78.74	76.26	73.78	71.32	68.86	66.41
2050.	79.00	76.51	74.03	71.56	69.10	66.64
2060.	79.26	76.76	74.28	71.80	69.33	66.87
2070.	79.52	77.02	74.53	72.05	69.57	67.11
2080.	79.78	77.27	74.78	72.29	69.81	67.34
2090.	80.04	77.53	75.03	72.53	70.05	67.57
2100.	80.29	77.78	75.28	72.78	70.28	67.80
2110.	80.55	78.04	75.52	73.02	70.52	68.03
2120.	80.81	78.29	75.77	73.26	70.76	68.26
2130.	81.07	78.54	76.02	73.50	70.99	68.49
2140.	81.33	78.80	76.27	73.75	71.23	68.72
2150.	81.59	79.05	76.52	73.99	71.47	68.95
2160.	81.85					
2170.	82.11					
2180.	82.37					
2190.	82.62					
2200.	82.88					
2210.	83.14					
2220.	83.40					
2230.	83.66					
2240.	83.92					
2250.	84.17					
2260.	84.43					
2270.	84.69					
2280.	84.95					
2290.	85.20					
2300.	85.46					
2310.	85.72					
2320.	85.98					
2330.	86.24					
2340.	86.49					
2350.	86.75					
2360.	87.01					
2370.	87.26					
2380.	87.52					
2390.	87.78					
2400.	88.04					
2410.	88.29					
2420.	88.55					

Table 3. The viscosity of nitrogen, oxygen, and their binary mixtures --Continued

Temperature	Viscosity (μPa s)					
T (K)	Mole fraction of nitrogen, X $_{N_2}$					
	0.0	0.2	0.4	0.6	0.8	1.0
2430.	88.81					
2440.	89.07					
2450.	89.32					
2460.	89.58					
2470.	89.84					
2480.	90.10					
2490.	90.35					
2500.	90.61					
2510.	90.87					
2520.	91.13					
2530.	91.38					
2540.	91.64					
2550.	91.90					
2560.	92.15					
2570.	92.41					
2580.	92.67					
2590.	92.93					
2600.	93.19					

6. Universal Correlation

A series of accurate measurements of the viscosity of some 20 pure gases and many of their binary mixtures within the temperature range 300–970 K has made it possible to develop a simple, unified scheme for their correlation.[4] The scheme, which is again based upon the kinetic theory of dilute gases, makes use of the hypothesis that the functional Ω_η^* is universal among all the pair interactions among the various species. This means that the viscosity of any pure
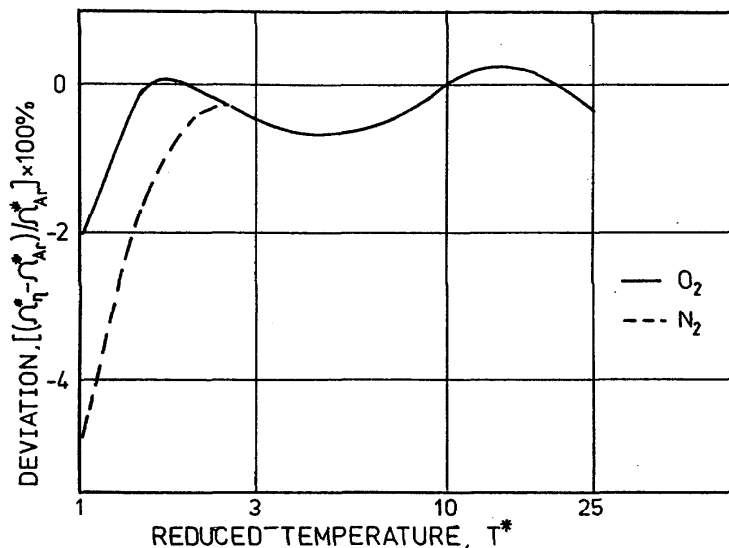

FIG. 9. Differences between the functional Ω_η^* for nitrogen and oxygen, and that for argon.

Table 4. The scaling parameters for the universal correlation

(a) The energy scaling parameter e/k (K):

	N_2	O_2
N_2	100.5	109.9
O_2		125.6

(b) The length scaling parameter s (nm):

	N_2	O_2
N_2	0.3646	0.3516
O_2		0.3387

gas, binary or multicomponent mixture, may be expressed in terms of just two universal correlations of the kinetic theory functionals Ω_η^* and A_{12}^* and a pair of scaling parameters for each binary interaction. The simplicity of this correlation scheme makes it particularly attractive for routine computational work. However, at the same time, it must be recognized that the hypothesis of universality is not confirmed exactly by experimental data. For example, Fig. 9 shows a plot of the deviations of the optimum functionals Ω_η^* for nitrogen and oxygen, deduced in the present study from that for argon.[32] Above a reduced temperature of $T^* = 3$ the deviations are very small, although noticeably systematic; but below this temperature the functionals for nitrogen and oxygen depart markedly each other and from that for argon.

Although these differences of behavior are of fundamental interest, from the practical point of view they are small enough that the advantages of simplicity which accrue from their neglect may be sufficient to outweigh the marginal loss of accuracy which results. Accordingly, we have cho-

sen to provide an additional, simplified correlation of the viscosity of nitrogen, oxygen, and their binary mixtures using the extended principle of corresponding states.[4] For this purpose we have represented the primary data for each system by means of the universal correlations[4]

$$\ln[^u\Omega^*(T')] = 0.466\ 49 - 0.570\ 15(\ln T')$$
$$+ 0.191\ 64(\ln T')^2$$
$$- 0.037\ 08(\ln T')^3 + 0.002\ 41(\ln T')^4, \quad (11)$$

where

$$1.0 \leqslant T' \leqslant 90,$$

for Ω_η^* and Eq. (10) for A_{12}^*, in conjunction with the kinetic theory results of Eqs. (1), (6), and (8). This representation has been achieved by means of the selection of an optimum pair of scaling parameters for each interaction in the same way as before. In this case we denote the energy scaling parameters by e, so that

$$T' = kT/e, \quad (12)$$

and the length scaling parameter by s in order to distinguish from those of the previous correlation. The optimum values of e and s are listed in Table 4.

Figure 10 contains a plot of the deviations of the primary experimental data for nitrogen, oxygen, and their mixtures from this universal correlation. The maximum deviation is now one of $\pm 3.5\%$, whereas the standard deviation is $\pm 0.4\ \mu$Pa s. These values are slightly greater than the corresponding values for the optimum correlation. However, the universal correlation is able to represent the tabulated viscosity for the nitrogen–oxygen system with a deviation of no more than $\pm 0.6\%$, so that for many purposes it
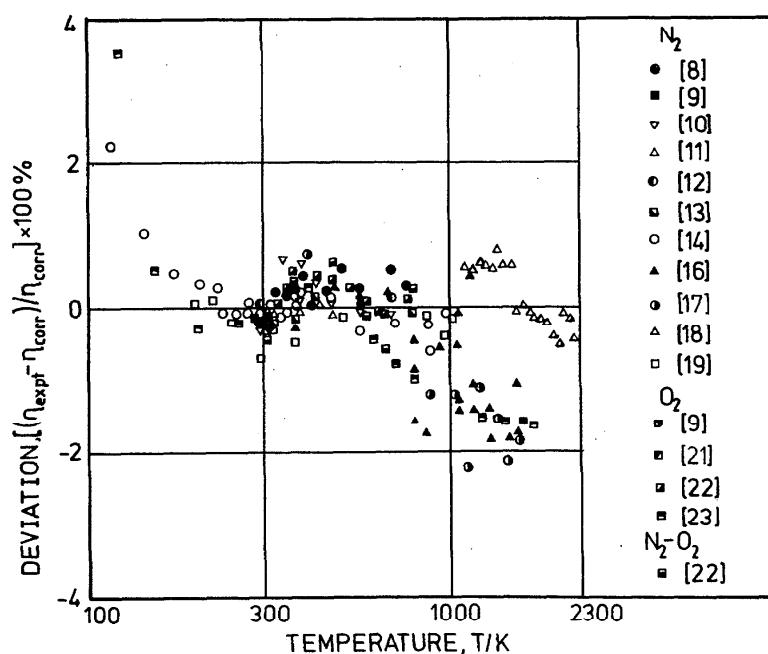

FIG. 10. Deviations of the primary viscosity data for nitrogen, oxygen, and their mixtures from the universal correlation.

is sufficiently accurate. In view of the fact that the correlation of the universal functional $^u\Omega_\eta^*$ is applicable over the reduced temperature range $1.0 \leqslant T' \leqslant 90$, it is also possible to extrapolate the viscosity of the same systems beyond the range of the optimum correlation (up to 11 500 K in the case of oxygen). Inevitably, the accuracy of this extrapolation is likely to be poorer than that characteristic of the region of the experimental data but the proposed procedure undoubtedly provides the most secure method of effecting the extension.

7. Conclusions

A concise representation of the viscosity of nitrogen, oxygen, and their binary mixtures in the limit of zero density has been presented. An optimum correlation of the experimental data has permitted the representation and tabulation of the viscosity with an accuracy of no more than ± 0.5% in the temperature range 290–1000 K. Outside of this temperature range, the uncertainty is greater but still does not exceed ± 2% over the range 110–2100 K for the pure gases, although for the mixtures it may rise to as much as ± 3% at the lowest temperatures.

A simplified, universal correlation is able to represent the tabulated data with a maximum deviation of ± 0.6% which permits the viscosity to be evaluated in an even wider temperature range although with some loss of accuracy.

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9. References

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