The viscosity and thermal conductivity of pure monatomic gases from their normal boiling point up to 5000 K in the limit of zero density and at 0.101325 MPa

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The viscosity and thermal conductivity of pure monatomic gases from their normal boiling point up to 5000 K in the limit of zero density and at 0.101325 MPa

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The kinetic theory of gases in the limit of zero density and that of moderately dense gases is used to generate accurate tables of the viscosity and thermal conductivity of the pure monatomic gases for zero density and for a pressure of 0.101325 MPa. The theoretically-based tables cover the temperature range from the normal boiling point of the relevant gas up to 5000 K. The associated uncertainties of the proposed data are detailed in the paper. A comparison of the correlated data with experimental results and some other recent correlations is given.

Key words: argon; helium; krypton; monatomic gases; neon; thermal conductivity of gases; transport properties; viscosity of gases; xenon.

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1. Introduction

The existence of a sophisticated kinetic theory for zero-density gases, in conjunction with the progress that has been made with respect to high-precision measurements of the transport properties of gases, has provided the basis for the development of extensive and accurate correlations and predictions for the viscosity and thermal conductivity of many simple gases and gas mixtures. In general, one can differentiate between so-called universal correlations using the extended principle of corresponding states [1–6] on one hand and so-called individual correlations [7–11]. These correlations for transport properties in the limit of zero density naturally include monatomic gases [1–3,6]. Most of these recent studies follow the guidelines worked out by the Subcommittee on Transport Properties of IUPAC Commission I.2, as does this work.

The justification for an up-to-date evaluation of the transport properties of the monatomic gases derives from recent theoretical as well as experimental results. For instance, during the last three years an almost conformal set of HFD-B type interatomic potentials has been developed[12–15]. This forms the essential basis for our zero-density data.

The development of an improved kinetic theory of moderately dense gases[16,17] and its experimental verification[18–21] enables the initial density dependence of the transport coefficients to be evaluated. As shown later, this effect amounts to several per cent especially at low temperatures. Finally, there are numerous new high-precision data for the thermal conductivity measured using transient hot-wire techniques. At the same time, new shock tube measurements have become available[22] which extend the temperature range considerably. In connection with these results it is shown that shock tube data for helium and neon in agreement with general theoretical results[23–25] are burdened with systematic errors due to thermal accomodation (temperature jump effect) at very high temperatures. Analogously, high-temperature viscosity data of the light noble gases should be influenced by the slip effect. The mentioned theoretical and experimental progress has formed the basis for the proposed tables from the normal boiling point of the relevant gas up to 5000 K. The tables include data at zero-density and for a standard pressure of 0.101325 MPa. The reliability of the correlation scheme used is confirmed by comparison of correlated data with experimental results at experimental pressures (densities).

2. Kinetic Theory

2.1. General

In the case of transport properties it is conventional to express the properties in the form

$$X(\rho,T) = X_0(T) + \Delta X(\rho,T) + \Delta X_c(\rho,T) \qquad (1)$$

The term $X_0(T)$ represents the viscosity ($X=\eta$) or thermal conductivity ($X=\lambda$) in the limit of zero-density, while the term $\Delta X(\rho,T)$ represents the excess property and $\Delta X_c(\rho,T)$ is its critical enhancement. Here, we are only concerned with the viscosity and thermal conductivity outside the critical region, i.e. $\Delta X_c(\rho,T) = 0$. On the other hand, we have to take into account the possibility of significant quantum effects for the light monatomic gases. Since such effects are to be expected with respect to $X_0(T)$ as well as $\Delta X(\rho,T)$, we define for practical purposes $X_0(T)$ and $\Delta X(\rho,T)$ as the classical contributions to the transport coefficients and add quantum correction terms. Thus, we get

$$X(\rho,T) = X_0(T) + \Delta X(\rho,T) + X_{0,QM}(T) + \Delta X_{QM}(\rho,T). \qquad (2)$$

The treatment of the individual contributions is detailed in the following chapters.

2.2. The Classical Zero-density Contribution

The classical zero-density contribution always forms the basic contribution to the transport properties in the density region we are dealt with in this study. We have decided to base our tables on data that have been calculated from the interatomic potentials. Starting from our older results[26,27] we have used the recently proposed almost conformal HFD-B type potentials[12–15]. These potentials are generated on a sound theoretical basis and

have been optimized using a large number of microscopic as well as macroscopic properties including data for viscosity and thermal conductivity.

It is this multiproperty fit that makes sure that the proposed potentials are useful throughout the entire temperature range. Following this philosophy, we have calculated $\eta_0(T)$ and $\lambda_0(T)$ according to the Chapman-Enskog theory[28], i.e.

$$\eta_0 = 0.026696\ (TM)^{1/2} f_\eta^{(k)} / (\sigma^2\, \Omega^{(2,2)^*}(T^*)) \tag{3}$$

and

$$\lambda_0 = 0.83236\ (T/M)^{1/2} f_\lambda^{(k)} / (\sigma^2\, \Omega^{(2,2)^*}(T^*)). \tag{4}$$

Here, $T^* = kT/\epsilon$, ϵ/k represents the potential well depth, σ the collision diameter, M the molar mass, k Boltzmann's constant and $\Omega^{(2,2)^*}(T^*)$ the reduced collision integral.

$f_\eta^{(k)}$ and $f_\lambda^{(k)}$ are the higher order correction factors. We have applied the second order Kihara approximation[28]

$$f_\eta^{(2)} = 1 + \frac{3}{196}(8E^* - 7)^2 \tag{5}$$

and

$$f_\lambda^{(2)} = 1 + \frac{1}{42}(8E^* - 7)^2, \tag{6}$$

with the dimensionless collision integral ratio E^*. The needed potential parameters have been taken from Ref. 14 (He), Ref. 15 (Ne), Ref. 12 (Ar, Kr) and Ref. 13 (Xe).

2.3. The Initial Density Dependence

The contribution of the initial density dependence $X_1(\rho,T)$ to the excess property $\Delta X(\rho,T)$ is usually combined with the zero-density contribution $X_0(T)$ according to

$$\eta(\rho,T) = \eta_0(T) + \eta_1(\rho,T) + \ldots = \eta_0(1 + B_\eta \rho + \ldots) \tag{7}$$

and

$$\lambda(\rho,T) = \lambda_0(T) + \lambda_1(\rho,T) + \ldots = \lambda_0(1 + B_\lambda \rho + \ldots). \tag{8}$$

The so-called 2nd viscosity and thermal conductivity virial coefficients B_η and B_λ consist of three contributions:

$$B_{\eta,\lambda} = B_{\eta,\lambda}^{(2)} + B_{\eta,\lambda}^{(3)} + B_{\eta,\lambda}^{(M-D)}. \tag{9}$$

$B_{\eta,\lambda}^{(2)}$ represents a two-monomer contribution, $B_{\eta,\lambda}^{(3)}$ a three- monomer contribution and $B_{\eta,\lambda}^{(M-D)}$ a monomer-dimer contribution. According to the theory of Rainwater and Friend[16,17] $B_\eta^{(3)} = B_\lambda^{(3)}$, whereas the other contributions are different for viscosity and thermal conductivity. The monomer-dimer terms are based on the assumption that the effective monomer-dimer potential is of a Lennard-Jones 12–6 type as it is assumed for the monomer-monomer interaction. Additionally, the ratio of energy scales

$$\theta = \epsilon_{M-D}/\epsilon_M \tag{10a}$$

and that of length scales

$$\delta = \sigma_{M-D}/\sigma_M \tag{10b}$$

have been introduced. Rainwater and Friend[16,17] have exactly calculated $B_{\eta,\lambda}^{(2)}$. $B_{\eta,\lambda}^{(3)}$ is given in a first approximation. Finally, Rainwater and Friend[16] have adjusted $B_{\eta,\lambda}^{(M-D)}$ to experimental data summarized by Hanley *et al.*[29] by means of

$$\theta = 1.15 \quad ; \quad \delta = 1.02\,. \tag{11}$$

Using the recent data of Refs. 18–21 as well as other experimental material Bich and Vogel[30] have improved the potential parameter ratios θ and δ and therefore the related monomer-dimer contributions. The $B_\eta^{(M-D)}$ and $B_\lambda^{(M-D)}$ and the total second transport virial coefficients (B_η, B_λ) of this work are based on

$$\theta = 1.25 \text{ and } \delta = 1.04 \tag{12}$$

and have been used throughout this paper.

2.4. Quantum Corrections

2.4.1. Quantum Corrections to the Zero-density Transport Coefficients

In the case of helium and neon it is necessary to include quantum corrections to the zero-density transport coefficients. In fact, these contributions have been calculated using complicated phase shift routines as detailed in Refs. 14, 15, 31. By comparison with the classically calculated collision integrals it has turned out that quantum effects play a significant role up to 400 K for helium as well as for neon. Since the calculation of the quantum mechanical collision integrals is rather cumbersome, we have used a basis set of these data as a function of temperature to evaluate correlation equations for $X_{0,QM}(T)$. Those have enabled the correction term to be calculated for any temperature. The effect of quantum corrections to the zero-density transport properties is demonstrated in Fig. 1.

2.4.2. Quantum Corrections to the Initial Density Dependence

Again, quantum corrections for helium and neon should be taken into account. There is only little theoretical work concerning this problem. In this study we have assumed that the contributions of quantum effects to the density dependence of the transport coefficients of neon are negligible within the stated uncertainty of the proposed data. The situation is different for helium: One

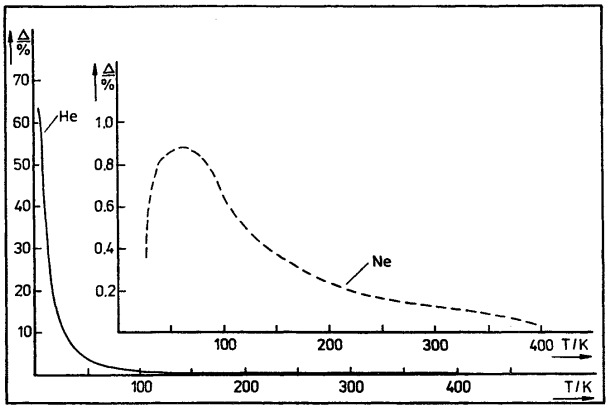

FIG. 1. Relative contribution of quantum effects to the zero-density viscosity of helium and neon.

can assume that the quantum-mechanically calculated monomer-dimer term for helium at low temperatures is small (c.f. Ref. 14). There are no detailed results for $B_{\eta,\lambda}^{(2)}$ and $B_{\eta,\lambda}^{(3)}$ in the open literature. But, it is known from Refs. 32 and 33 that one has to include an additional term to Eq.(9) that accounts for the needed change from Boltzmann's to Bose-Einstein statistics in the case of ^{4}He. The classically computed values for $B_\lambda^{(2)}$and $B_\lambda^{(3)}$ below $T^* = 1.0$ add to negative values.The last mentioned additional term is also negative and $B_\lambda^{(M-D)}$ is small. Thus, the overall effect of the classical contribution to the initial density dependence of λ should be negative. The experimental results of Acton and Kellner[34] as well as those of Roder[35] on the other hand show positive values for B_λ. This clearly indicates a strong effect of quantum corrections at very low temperatures. As a consequence of this fact we have correlated the initial density dependence of the thermal conductivity of helium below 100 K using the experimental results of Refs. 34 and 35. Above 100 K the quantum corrections to $X_1(\rho,T)$ become negligible. This effect is shown in Fig. 2. Since there are no comparable measurements for viscosity, we have used the classically calculated initial density dependence above 20 K. This corresponds to larger uncertainties in η in the temperature range 20–100 K. Between 5 and 20 K only zero-density values including the quantum correction to $\eta_0(T)$ are given.

3. Experimental Data

From a direct comparison of the entire data set of published transport property data for the monatomic gases, it is obvious that there are substantial discrepancies between various author's results (c.f. Refs. 1–3, 6, 26). Apparently, it is extremely difficult to decide on the accuracy of reported data solely on the basis of the available literature. Therefore, we have employed two complementary methods of assessing, in particular, the older experimental data. First, we have used a comparison with new experimental data measured with improved modern equipment of proven accuracy (viscosity: oscillating-disc viscometers or capillary viscometers, if a complete working theory has been applied; thermal conductivity: transient hot-wire cells). Secondly, we have attempted to establish confidence in experimental data by recourse to the available kinetic theory[1-3,6,26,28]. That means, we have used a consistency test using a comparison of experimental data with results calculated from interatomic potentials and an extended law of corresponding states analysis. Thus, we have commenced

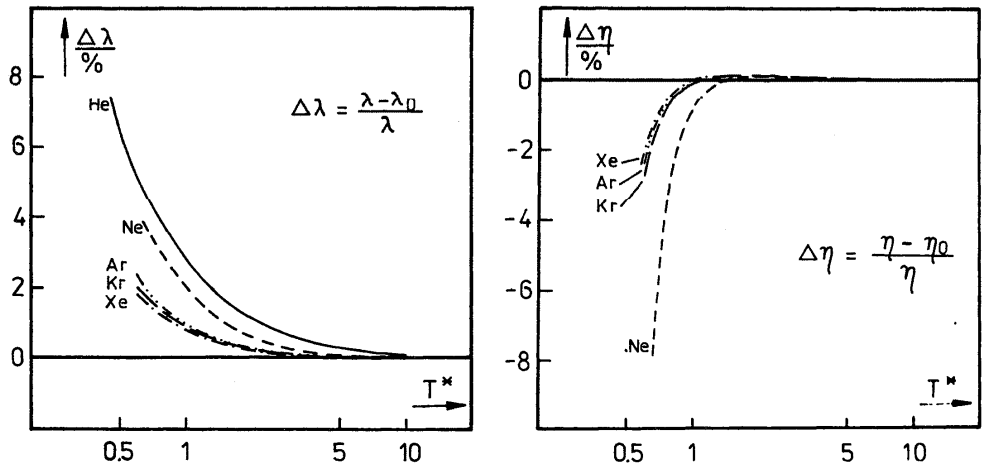

FIG. 2. Relative contribution of the initial density dependence to the viscosity and thermal conductivity of monatomic gases.

our study by dividing the experimental data into the categories of primary and secondary data[7-9,36].

Under primary data we consider experimental data measured with apparatus of high precision for which a complete working equation and a detailed knowledge of all corrections are available. In most cases this would unduly reduce the temperature range studied. Therefore, we have also included such data in our basis set which prove consistent with the high-precision data and theoretical results as outlined before.

Secondary data are the results of measurements which are of inferior accuracy to primary data. This inferior accuracy may arise from incomplete characterization of the apparatus or from operation at extreme conditions. From Sec. 2 it becomes apparent that one always needs the characterization of transport property data as a function of temperature *and* density (or pressure). Therefore, under secondary data we also consider experimental results without any information about the applied density or pressure.

For the five monatomic gases, we have carried out a survey of the available data and assigned them to one of the categories mentioned above. Only primary data were used in the formulation of the tables and for the purpose of comparison. The finally selected basis sets for viscosity and thermal conductivity are detailed in Table 1 and Table 2, respectively. The tables include information about our estimate of the uncertainty of each datum. It is necessary to mention that in general only one set of a group has been included if there are several publications of data measured with the same instrument in the same temperature range and showing very similar general trends.

In the interest of brevity, we have not been comprehensive in collating the information about secondary data and have used for our comparisons instead some earlier representations in which these data were included.

4. Results

4.1. Comparison of Recommended Values with Experimental Data

The recommended data of this study (Tables 5–9) are compared to the primary data sets in Figs. 3–7 (viscosity) and Figs. 8–14 (thermal conductivity). The maximum deviations are also included in Tables 1 and 2. All deviations are calculated at experimental pressures (densities) or for zero density if the usual statistical analysis of data as a function of density has been applied in order to obtain values appropriate to the zero-density limit. The agreement of almost the entire data set with the recommended values is well within the claimed accuracy of the tables (c.f. Table 4).

It is worth noting that there are significant deviations for the thermal conductivity of helium and neon determined using shock tube measurements. This result can be explained qualitatively by means of the theory of thermal accomodation (temperature jump effects)[23-25]. The experimental results have not been corrected for this effect. Since there are neither the needed complete information about the measurements nor exact working equations for these corrections, we have used the originally published data for the purpose of comparison. A rough estimate shows that the calculated deviations are significantly reduced if such corrections are applied. (The systematic deviation of the results of Collins *et al.*[66] for krypton is obviously due to badly chosen calibration data.) The same as for the influence of temperature jump effects on thermal conductivity measurements seems to be true to a smaller extent for results of high temperature viscosity measurements carried out with capillary viscometers.

4.2 Comparison with Earlier Correlations

We have included comparisons with some earlier correlations in Figs. 3–15. The agreement with the corresponding states analysis of Kestin *et al.*[3] (zero-density (z.d.) values only) is good for all gases. From Fig. 15 it becomes obvious that the agreement with our correlation is within ± 1% in the temperature range 300 K < T < 2000 K and rises to maximum ± 2% at either temperature extreme. This is shown for the viscosity only, but, since thermal conductivity was calculated using the same collision integral, it is also true for this quantity.

We also have compared our results to correlations of Refs. 69–74. With the exception of helium and neon the agreement with earlier work is satisfactory; generally, the larger differences have appeared below $T^* = 1$. Furthermore, the results for helium (Fig. 4 , Ref. 69) indicate that a Lennard-Jones 12–6 potential is not suitable to deduce reliable transport coefficients covering a large temperature range including quantum effects. Finally, it has become evident that particularly for the light gases at very low temperatures there is a great need for further experimental work.

Hoshino *et al.*[75] recently published a correlation for the thermal conductivity of argon in the temperature range 300–4500 K that has been based on new shock tube measurements and data from the literature. The agreement of their result with recent shock tube measurements, with our correlation as well as with that of Kestin *et al.*[3] is rather poor above 1000 K. Using Eq. (16) and the related coefficients given in Ref. 75 we have found increasing differences with increasing temperature. These amount to about 11 per cent at 4500 K. This positive difference cannot be explained by temperature jump effects. We do not have a detailed explanation of this fact but it could also be caused by a badly chosen selection of calibration data at 1000 K for the author's experiments.

4.3. Corresponding States Analysis

As shown in Ref. 6, a two parameter theorem of corresponding states is useful with respect to the zero-density transport coefficients in the range 1.0 < T^* < 35.

Naturally, the primary data set selected in this study is applicable to reanalyse this result and to check the consistency of our zero-density results. Moreover, this formalism provides a simple way to express the correlated data analytically within the given temperature range.

From Eqs. (3)–(6) a universal functional $\Omega_{\eta,\lambda}$ follows with scaling factors ϵ/k and σ which are not identical with the potential parameters ϵ/k and σ given in Eqs. (3)–(6):

$$\Omega_{\eta,\lambda} = \frac{0.026696\,(TM)^{1/2} f_\eta^{(k)}}{\eta_0 \sigma^2} = \frac{0.83236\,(T/M)^{1/2} f_\lambda^{(k)}}{\lambda_0 \sigma^2} \quad (13)$$

Analogously to Refs. 1–3, 6 and 28 we have used the following form in order to represent the temperature dependence of the universal functional

$$\Omega_{\eta,\lambda} = \exp \sum_{i=0}^{4} a_i (\ln T^*)^i . \quad (14)$$

TABLE 1. Sources of experimental data for the viscosity of monatomic gases

Paper	Temp. range (K)	Press. range (kPa)	No. of points	Acc. (%)	Max. dev. (%)	Method[a]
Helium						
Coremans[37 b]	20–80	13	7	2.0	1.1	OD
Kestin[38]	298–973	100	8	0.3–0.7	0.6	OD
Vogel[39]	298–623	100	6	0.3–0.5	0.2	OD
Becker[40 b]	14–20	0.3	5	3.0	1.9	OC
Dawe[41]	293–1600	100	15	1.0–2.0	−1.9	C
Gough[42]	120–320	15–65	11	1.7–1.0	1.8	C
Guevara[43]	1100–2150	80	22	1.0–3.0	−3.0	C
Neon						
Coremans[37 b]	20–80	4	7	2.0	1.9	OD
Kestin[38]	298–973	100	8	0.3–0.7	0.6	OD
Vogel[39]	298–623	100	6	0.3–0.5	−0.04	OD
Dawe[41]	293–1600	100	15	1.0–1.5	−2.7	C
Clarke[44]	77–374	20–60	10	1.5–1.0	1.3	C
Guevara[45]	1100–2100	80	21	1.0–1.5	−2.6	C
Argon						
Kestin[38]	298–973	100	8	0.3–0.7	0.7	OD
Vogel[39]	298–623	100	6	0.3–0.5	−0.1	OD
Dawe[41]	293–1600	100	15	1.0–1.5	−1.2	C
Gough[42]	120–320	15–65	11	1.7–1.0	0.7	C
Guevara[43]	1100–2100	80	21	1.0–1.5	1.0	C
Lyusternik[46]	403–1950	100	17	1.5	−1.5	P
Krypton						
Kestin[38]	298–973	100	8	0.3–0.7	0.6	OD
Vogel[39]	298–623	100	6	0.3–0.5	−0.2	OD
Dawe[41]	293–1600	100	15	1.0–1.5	−1.8	C
Gough[42]	120–320	15–65	11	1.7–1.0	0.7	C
Goldblatt[47]	1100–2000	80	10	1.0–1.5	−0.8	C
Xenon						
Kestin[38]	298–973	100	8	0.3–1.0	1.2	OD
Vogel[39]	298–623	100	6	0.3–0.5	0.1	OD
Dawe[41]	293–1600	100	15	1.0–1.5	1.1	C
Clarke[48]	176–375	40–60	9	1.5–1.0	0.3	C
Goldblatt[49]	1100–2000	80	10	1.0–1.5	0.8	C

[a]C – capillary, OD – oscillating disc, OC – oscillating cup, P – porous medium.
[b]Data of Refs. 37 and 40 have been recalculated using a calibration value deduced from the thermal conductivity given in Ref. 34 at 20 K and zero-density.

TABLE 2. Sources of experimental data for the thermal conductivity of monatomic gases

Paper	Temp. range (K)	Press. range (kPa)	No. of points	Acc. (%)	Max. dev. (%)	Method[a]
Helium						
Johns[50]	315–378	0	2	0.5–1.0	0.2	THW
Assael[51]	308	0	1	0.5	−0.1	THW
Kestin[52]	301	0	1	0.5	−0.03	THW
Mustafa[53]	308–428	0	4	0.7–1.5	1.5	THW
Haarman[54]	328–468	100	8	1.0	−0.4	THW
Vargaftik[55]	310–1238	100	12	2.0	−2.5	HW
Marchenkov[56]	407–1413	100	5	2.0	−3.3	HW
Shashkov[57]	92–274	100	15	2.0	−2.5	HW
Ubbink[58]	15–89	50	7	3.0	−2.3	PP
Acton[34]	5–20	0	10	1.0	1.2	PP
	5–20	100	10	1.0	−0.6	PP
Roder[35]	20–282	0	15	2.0	1.3	PP
	20–282	100	15	2.0	1.3	PP
Le Neindre[59]	297–775	100	7	2.0	1.5	CC
Faubert[60]	800–2100	100	14	4.0–3.0	−3.9	C
Collins[61]	1600–6700	60–200	11	4.0–15.0	−15.9	ST
Semlyanikh[62]	1000–4000	100	5	6.0–20.0	−10.5	ST
Neon						
Assael[51]	308	0	1	0.5	0.0	THW
Kestin[52]	301	0	1	0.5	−0.3	THW
Haarman[54]	328–468	100	8	1.0	−0.6	THW
Millat[63]	308–428	0	4	0.5–1.0	−0.8	THW
Nesterov[64]	90–273	100	20	1.5	−0.9	HW
Springer[65]	1000–1500	100	6	2.0	−0.6	C
Mastovsky[22]	1500–6000	100	10	8.0	−6.8	ST
Collins[66]	1500–5000	30–270	8	4.0–15.0	−11.5	ST
Argon						
Johns[50]	313–470	0	5	0.5–1.0	0.5	THW
Assael[51]	308	0	1	0.5	0.2	THW
Kestin[52]	301	0	1	0.5	−0.2	THW
Haarman[54]	328–468	100	8	1.0	−0.6	THW
Shashkov[57]	94–271	100	13	2.5–2.0	3.4	HW
Vargaftik[67]	311–1201	100	18	2.0	−2.3	HW
Springer[65]	1000–2500	100	16	2.0–1.5	−1.0	C
Mastovsky[22	1500–7000	100	12	8.0	−2.3	ST
Collins[66]	1500–5000	30–270	8	4.0–15.0	−3.8	ST
Krypton						
Assael[51]	308	0	1	0.5	−0.2	THW
Kestin[52]	301	0	1	0.5	−0.3	THW
Haarman[54]	328–468	100	8	1.0	−0.5	THW
Nesterov[64]	120–273	100	17	2.5–2.0	3.3	HW
Faubert[68]	800–2000	100	13	2.0	2.5	C
Mastovsky[22]	1500–7000	100	12	8.0	−2.4	ST
Collins[66]	1500–5000	30–270	8	4.0–15.0	−12.2	ST
Xenon						
Assael[51]	308	0	1	0.5	−0.1	THW
Kestin[52]	301	0	1	0.5	−0.3	THW
Shashkov[57]	195–272	100	7	2.5–2.0	4.5	HW
Springer[65]	1000–1500	100	6	2.0	−1.3	C
Mastovsky[22]	1500–7000	100	12	8.0	−1.6	ST

[a]THW – transient hot wire, HW – hot wire, ST – shock tube, C – column method, PP – parallel plates, CC – concentric cylinders

Our results for the coefficients a_i and the scaling factors ϵ/k and σ obtained by fitting Eq. (14) to experimental zero-density transport coefficients η_0 and λ_0 are given in Table 3.

Consistent data for η_0 and λ_0 lead via Eq.(13) to identical values of the universal functional. In our procedure the values of the correction factors $f_\eta^{(k)}$ and $f_\lambda^{(k)}$ have been chosen according to the corresponding HFD-B potentials given above although these corrections do not depend on the potential to a large extent. They represent a contribution of no more than 1% to the zero-density values in most cases. It is necessary to stress that this scheme is only applicable to *the classical part of zero-density transport properties*[30].

TABLE 3. Coefficients and scaling parameters for the corresponding states analysis ($1.0 < T^* < 35$)

Coefficients	
a_0	0.4422110
a_1	−0.5169991
a_2	0.1591556
a_3	−0.02888469
a_4	0.001575147

Scaling parameters		
Gas	ϵ/k (K)	σ (nm)
He	11.606	0.26072
Ne	41.491	0.27714
Ar	143.224	0.33528
Kr	206.91	0.35560
Xe	284.90	0.38810

TABLE 4. Relative uncertainties of recommended values (%)

T(K)	He	Ne	Ar	Kr	Xe
5	2.0				
20	1.5				
27.09		2.0			
80		1.0			
87.28			1.0		
100		1.0			
119.78				1.0	
165.03					1.0
290	0.5	0.5	0.5	0.5	0.5
298.15	0.3	0.3	0.3	0.3	0.3
300	0.5	0.5	0.5	0.5	0.5
700	0.5				
1000	1.0	0.5	0.5	0.5	0.5
1500		1.0			
2000	2.0	1.5	1.0	1.0	1.0
5000	5.0	3.0	2.0	2.0	2.0

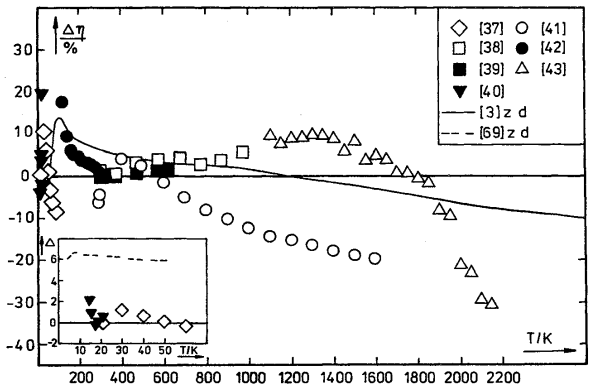

FIG. 3. Comparison of recommended viscosity values of helium to experimental results and earlier correlations.

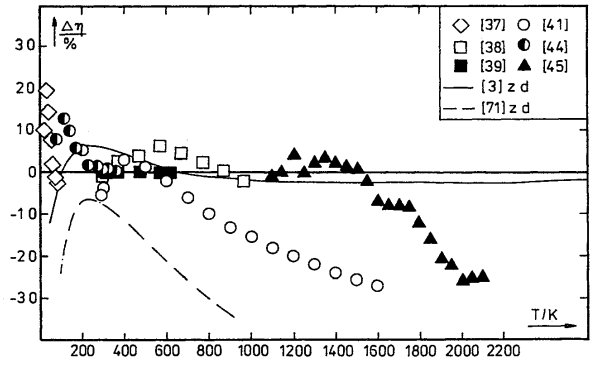

FIG. 4. Comparison of recommended viscosity values of neon to experimental results and earlier correlations.

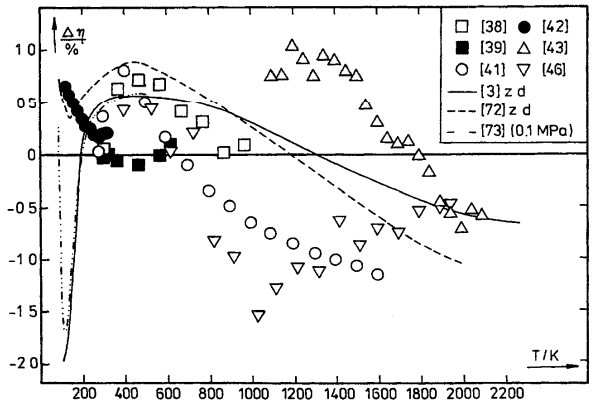

FIG. 5. Comparison of recommended viscosity values of argon to experimental results and earlier correlations.

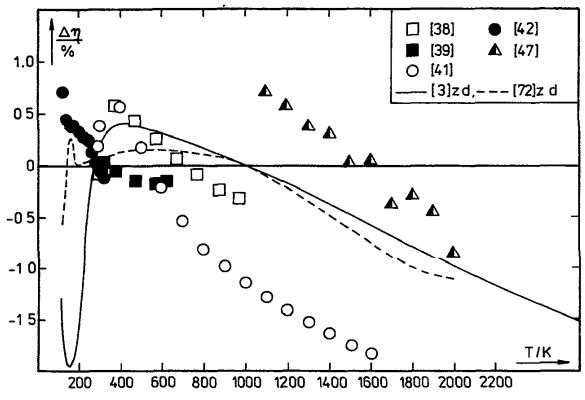

FIG. 6. Comparison of recommended viscosity values of krypton to experimental results and earlier correlations.

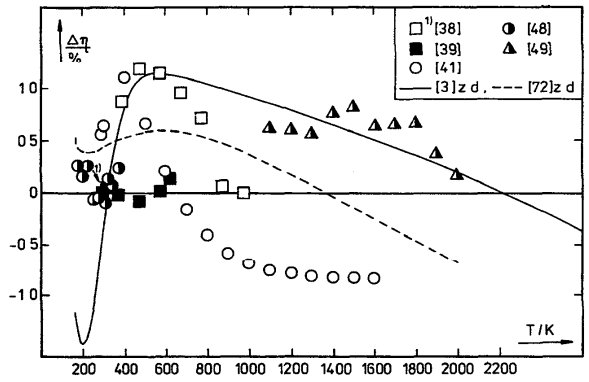

FIG. 7. Comparison of recommended viscosity values of xenon to experimental results and earlier correlations.

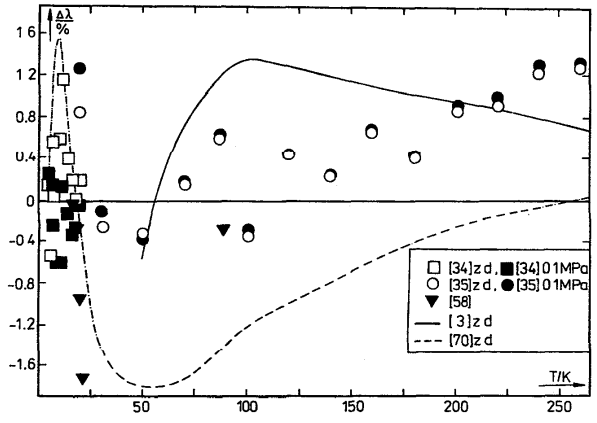

FIG. 8. Comparison of recommended thermal conductivity values of helium to selected experimental data and earlier correlations – temperature range 5–250 K.

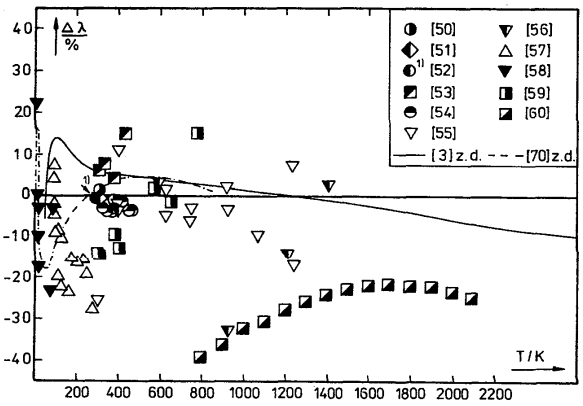

FIG. 9. Comparison of recommended thermal conductivity values of helium to experimental data and earlier correlations – up to 2100 K.

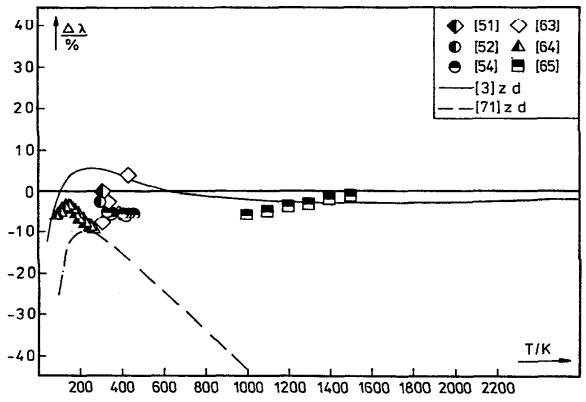

FIG. 10. Comparison of recommended thermal conductivity values of neon to experimental data and earlier correlations.

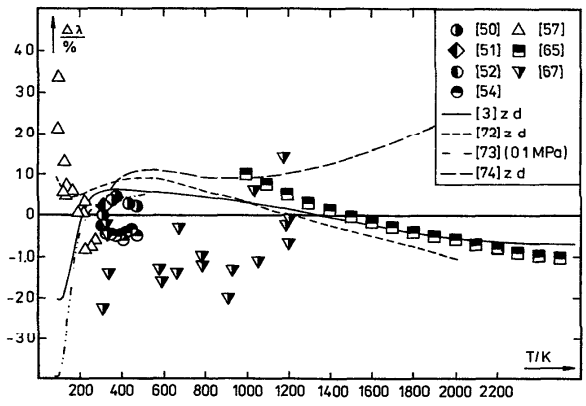

FIG. 11. Comparison of recommended thermal conductivity values of argon to experimental data and earlier correlations.

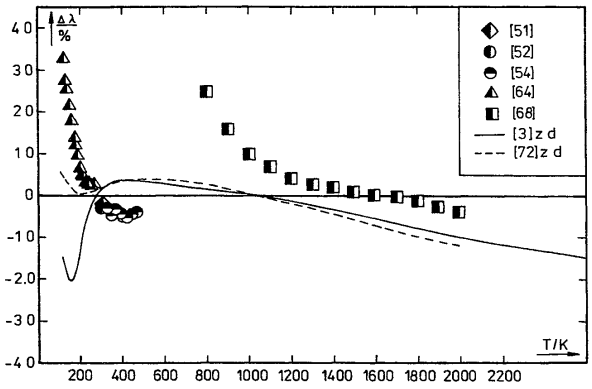

FIG. 12. Comparison of recommended thermal conductivity values of krypton to experimental data and earlier correlations.

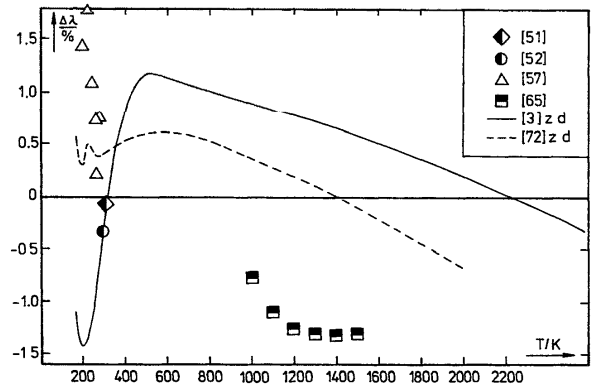

FIG. 13. Comparison of recommended thermal conductivity values of xenon to experimental data and earlier correlations.

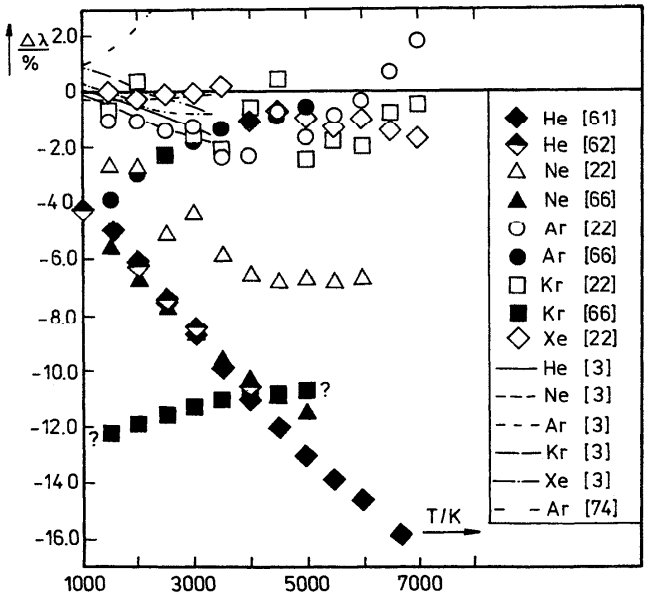

FIG. 14. Comparison of recommended high temperature thermal conductivities of monatomic gases to results of shock tube measurements and earlier correlations.

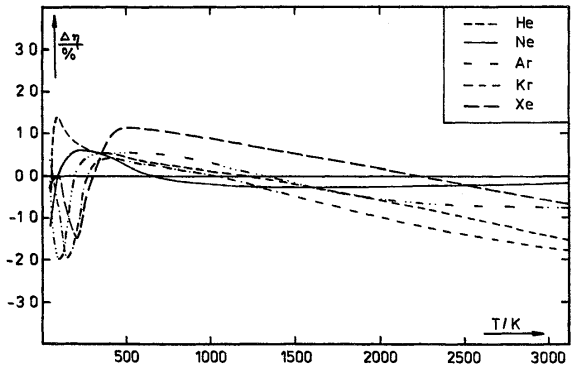

FIG. 15. Comparison of recommended zero-density viscosity data with values calculated using the corresponding states analysis by Kestin *et al.*

TABLE 5. The viscosity and thermal conductivity of helium

a) With contribution of initial density dependence

	Zero-density values		Values at 0.101325 MPa	
Temp. (K)	Viscosity (μPa s)	Therm. cond. (mW/m K)	Viscosity (μPa s)	Therm.cond. (mW/m K)
5	1.224	9.537		10.30
6	1.433	11.17		11.85
7	1.619	12.63		13.27
8	1.788	13.97		14.58
9	1.948	15.21		15.80
10	2.097	16.38		16.94
12	2.378	18.59		19.08
14	2.640	20.65		21.09
16	2.886	22.57		22.97
18	3.120	24.40		24.76
20	3.344	26.15	3.357	26.46
25	3.872	30.28	3.885	30.55
30	4.360	34.11	4.371	34.35
35	4.818	37.69	4.827	37.90
40	5.252	41.07	5.260	41.27
45	5.666	44.32	5.673	44.50
50	6.066	47.44	6.071	47.60
60	6.832	53.43	6.836	53.57
70	7.556	59.10	7.556	59.22
80	8.240	64.45	8.240	64.55
90	8.894	69.55	8.894	69.65
100	9.529	74.53	9.529	74.61
110	10.15	79.37	10.15	79.45
120	10.76	84.09	10.76	84.16
130	11.35	88.69	11.35	88.75
140	11.92	93.17	11.92	93.23
150	12.49	97.54	12.49	97.60
160	13.04	101.8	13.04	101.9

TABLE 5. The viscosity and thermal conductivity of helium — Continued

b) Negligible contribution of initial density dependence up to 0.101325 MPa

Temp. (K)	Viscosity (μPa s)	Therm. cond. (mW/m K)
170	13.58	106.0
180	14.11	110.2
190	14.63	114.2
200	15.14	118.2
210	15.64	122.2
220	16.14	126.1
230	16.63	130.0
240	17.12	133.8
250	17.60	137.5
260	18.08	141.2
270	18.54	144.9
273.15	18.69	146.0
280	19.01	148.5
290	19.47	152.1
298.15	19.84	155.0
300	19.92	155.7
320	20.82	162.7
340	21.70	169.6
360	22.57	176.4
380	23.43	183.1
400	24.27	189.6
420	25.09	196.0
440	25.91	202.5
460	26.72	208.8
480	27.52	215.1
500	28.32	221.3
550	30.27	236.5
600	32.17	251.3
650	34.03	265.9
700	35.86	280.1
750	37.65	294.2
800	39.42	307.9
850	41.16	321.5
900	42.87	334.9
950	44.56	348.1
1000	46.23	361.1
1050	47.89	374.0
1100	49.52	386.7
1150	51.14	399.4
1200	52.74	411.9
1250	54.33	424.2
1300	55.90	436.5
1350	57.46	448.7
1400	59.01	460.8
1450	60.55	472.8
1500	62.07	484.7
1550	63.59	496.5
1600	65.10	508.3
1650	66.59	519.9
1700	68.08	531.5
1750	69.56	543.1
1800	71.03	554.5
1850	72.50	566.0
1900	73.95	577.3
1950	75.40	588.6
2000	76.84	599.9
2050	78.28	611.1
2100	79.71	622.2
2150	81.13	633.3
2200	82.55	644.3
2250	83.96	655.4

TABLE 5. The viscosity and thermal conductivity of helium — Continued

b) Negligible contribution of initial density dependence up to 0.101325 MPa

Temp. (K)	Viscosity (μPa s)	Therm. cond. (mW/m K)
2300	85.37	666.3
2350	86.77	677.2
2400	88.16	688.1
2450	89.56	699.0
2500	90.94	709.8
2600	93.70	731.3
2700	96.44	752.6
2800	99.16	773.9
2900	101.9	795.0
3000	104.6	816.0
3100	107.2	836.9
3200	109.9	857.6
3300	112.6	878.3
3400	115.2	898.9
3500	117.8	919.4
3600	120.4	939.7
3700	123.0	960.0
3800	125.6	980.2
3900	128.2	1000.
4000	130.8	1020.
4100	133.4	1040.
4200	135.9	1060.
4300	138.6	1081.
4400	141.1	1101.
4500	143.7	1121.
4600	146.2	1140.
4700	148.7	1160.
4800	151.2	1180.
4900	153.7	1199.
5000	156.2	1218.

TABLE 6. The viscosity and thermal conductivity of neon

a) With contribution of initial density dependence

	Zero-density values		Values at 0.101325 MPa	
Temperature (K)	Viscosity (μPa s)	Therm. cond. (mW/m K)	Viscosity (μPa s)	Therm. cond. (mW/m K)
27.09	4.254	6.573	3.893	6.838
28	4.402	6.802	4.092	7.071
30	4.711	7.279	4.483	7.547
32	5.024	7.763	4.848	8.020
34	5.336	8.245	5.199	8.492
36	5.646	8.724	5.539	8.961
38	5.958	9.206	5.874	9.434
40	6.271	9.690	6.205	9.908
42	6.579	10.17	6.527	10.38
44	6.885	10.64	6.844	10.84
46	7.188	11.11	7.157	11.30
48	7.490	11.57	7.466	11.76
50	7.792	12.04	7.774	12.22
55	8.533	13.19	8.527	13.35
60	9.253	14.30	9.253	14.45
65	9.955	15.39	9.962	15.53
70	10.64	16.45	10.65	16.58
75	11.31	17.49	11.32	17.61

TABLE 6. The viscosity and thermal conductivity of neon – Continued

a) With contribution of initial density dependence

Temperature (K)	Zero-density values Viscosity (μPa s)	Zero-density values Therm. cond. (mW/m K)	Values at 0.101325 MPa Viscosity (μPa s)	Values at 0.101325 MPa Therm. cond. (mW/m K)
80	11.96	18.50	11.98	18.61
85	12.60	19.48	12.61	19.59
90	13.21	20.43	13.22	20.53
95	13.80	21.35	13.82	21.45
100	14.39	22.26	14.40	22.35
110	15.52	24.02	15.54	24.11
120	16.61	25.71	16.63	25.79
130	17.66	27.34	17.67	27.41
140	18.67	28.91	18.68	28.97
150	19.65	30.43	19.66	30.49
160	20.60	31.90	20.61	31.96
170	21.52	33.34	21.52	33.39
180	22.42	34.74	22.42	34.79
190	23.30	36.10	23.30	36.15
200	24.16	37.43	24.16	37.48
210	24.99	38.74	24.99	38.78
220	25.82	40.02	25.82	40.06
230	26.62	41.27	26.62	41.31
240	27.42	42.50	27.42	42.54
250	28.20	43.71	28.20	43.75
260	28.96	44.90	28.96	44.94
270	29.72	46.08	29.72	46.11
273.15	29.96	46.45	29.96	46.48
280	30.47	47.24	30.47	47.27
290	31.20	48.38	31.20	48.41
298.15	31.79	49.30	31.79	49.32
300	31.93	49.50	31.93	49.53
320	33.34	51.71	33.34	51.73

b) Negligible contribution of initial density dependence up to 0.101325 MPa

Temperature (K)	Viscosity (μPa s)	Therm. cond. (mW/m K)
340	34.73	53.86
360	36.09	55.96
380	37.41	58.02
400	38.70	60.02
420	39.98	62.01
440	41.24	63.97
460	42.48	65.89
480	43.71	67.79
500	44.91	69.66
550	47.85	74.22
600	50.71	78.64
650	53.48	82.95
700	56.19	87.14
750	58.83	91.24
800	61.42	95.25
850	63.95	99.18
900	66.44	103.0
950	68.89	106.8
1000	71.30	110.6

TABLE 6. The viscosity and thermal conductivity of neon – Continued

b) Negligible contribution of initial density dependence up to 0.101325 MPa

Temperature (K)	Viscosity (μPa s)	Therm. cond. (mW/m K)
1050	73.67	114.2
1100	76.00	117.9
1150	78.31	121.4
1200	80.58	125.0
1250	82.83	128.4
1300	85.05	131.9
1350	87.24	135.3
1400	89.41	138.6
1450	91.56	142.0
1500	93.68	145.3
1550	95.79	148.5
1600	97.87	151.8
1650	99.94	155.0
1700	102.0	158.1
1750	104.0	161.3
1800	106.0	164.4
1850	108.0	167.5
1900	110.0	170.6
1950	112.0	173.6
2000	113.9	176.6
2050	115.9	179.6
2100	117.8	182.6
2150	119.7	185.6
2200	121.6	188.5
2250	123.5	191.5
2300	125.4	194.4
2350	127.3	197.3
2400	129.1	200.1
2450	131.0	203.0
2500	132.8	205.8
2600	136.4	211.5
2700	140.0	217.1
2800	143.6	222.6
2900	147.1	228.0
3000	150.6	233.5
3100	154.1	238.8
3200	157.5	244.2
3300	160.9	249.4
3400	164.3	254.7
3500	167.7	259.9
3600	171.0	265.0
3700	174.3	270.1
3800	177.6	275.2
3900	180.8	280.3
4000	184.1	285.3
4100	187.3	290.3
4200	190.5	295.2
4300	193.7	300.1
4400	196.8	305.0
4500	200.0	309.9
4600	203.1	314.7
4700	206.2	319.5
4800	209.3	324.3
4900	212.4	329.1
5000	215.4	333.8

TABLE 7. The viscosity and thermal conductivity of argon

a) With contribution of initial density dependence

Temp. (K)	Zero-density values: Viscosity (μPa s)	Zero-density values: Therm. cond. (mW/m K)	Values at 0.101325 MPa: Viscosity (μPa s)	Values at 0.101325 MPa: Therm. cond. (mW/m K)
87.28	7.133	5.567	6.971	5.698
90	7.347	5.734	7.204	5.862
100	8.132	6.347	8.042	6.466
110	8.927	6.968	8.870	7.078
120	9.721	7.587	9.685	7.689
130	10.51	8.206	10.49	8.302
140	11.31	8.824	11.30	8.916
150	12.09	9.436	12.09	9.521
160	12.86	10.04	12.86	10.12
170	13.63	10.64	13.63	10.72
180	14.39	11.24	14.40	11.31
190	15.15	11.82	15.16	11.89
200	15.88	12.40	15.90	12.46
210	16.61	12.97	16.62	13.03
220	17.33	13.53	17.34	13.59
230	18.03	14.08	18.05	14.14
240	18.73	14.63	18.75	14.68
250	19.42	15.17	19.44	15.22
260	20.10	15.70	20.12	15.75
270	20.77	16.22	20.78	16.27
273.15	20.98	16.38	20.99	16.43
280	21.43	16.74	21.44	16.78
290	22.07	17.24	22.09	17.29
298.15	22.59	17.65	22.61	17.69
300	22.71	17.74	22.72	17.79
320	23.96	18.72	23.98	18.76
340	25.18	19.68	25.19	19.72
360	26.37	20.61	26.38	20.65
380	27.53	21.52	27.53	21.56
400	28.67	22.41	28.66	22.44
420	29.77	23.28	29.77	23.31
440	30.85	24.13	30.85	24.16
460	31.91	24.96	31.91	24.99
480	32.95	25.78	32.95	25.80
500	33.98	26.58	33.98	26.60
550	36.45	28.52	36.45	28.55
600	38.83	30.39	38.83	30.41
650	41.13	32.19	41.13	32.21
700	43.35	33.93	43.35	33.95

TABLE 7. The viscosity and thermal conductivity of argon — Continued

b) Negligible contribution of initial density dependence up to 0.101325 MPa

Temperature (K)	Viscosity (μPa s)	Therm. cond. (mW/m K)
750	45.50	35.62
800	47.60	37.28
850	49.64	38.88
900	51.63	40.43
950	53.58	41.97
1000	55.50	43.47
1050	57.37	44.93
1100	59.21	46.39
1150	61.02	47.80
1200	62.81	49.20
1250	64.56	50.58
1300	66.29	51.93
1350	68.00	53.28
1400	69.69	54.60
1450	71.35	55.90
1500	72.99	57.19
1550	74.62	58.46
1600	76.23	59.71
1650	77.82	60.97
1700	79.39	62.20
1750	80.95	63.41
1800	82.50	64.62
1850	84.02	65.82
1900	85.54	67.01
1950	87.04	68.20
2000	88.54	69.37
2050	90.02	70.51
2100	91.48	71.67
2150	92.94	72.80
2200	94.39	73.94
2250	95.82	75.07
2300	97.25	76.19
2350	98.66	77.29
2400	100.1	78.39
2450	101.5	79.49
2500	102.9	80.58
2600	105.6	82.72
2700	108.3	84.86
2800	111.0	86.96
2900	113.7	89.04
3000	116.3	91.10
3100	118.9	93.14
3200	121.5	95.17
3300	124.0	97.17
3400	126.6	99.14
3500	129.1	101.1
3600	131.6	103.1
3700	134.1	105.0
3800	136.5	106.9
3900	138.9	108.8
4000	141.4	110.7
4100	143.8	112.6
4200	146.1	114.4
4300	148.5	116.3
4400	150.9	118.1
4500	153.2	120.0
4600	155.5	121.8
4700	157.8	123.6
4800	160.1	125.4
4900	162.4	127.2
5000	164.7	128.9

TABLE 8. The viscosity and thermal conductivity of krypton

a) With contribution of initial density dependence

	Zero-density values		Values at 0.101325 MPa	
Temp. (K)	Viscosity (μPa s)	Therm. cond. (mW/m K)	Viscosity (μPa s)	Therm. cond. (mW/m K)
119.78	10.55	3.927	10.28	4.009
120	10.57	3.934	10.30	4.016
130	11.42	4.248	11.22	4.327
140	12.26	4.563	12.12	4.637
150	13.12	4.880	13.01	4.951
160	13.97	5.199	13.90	5.267
170	14.83	5.517	14.77	5.582
180	15.68	5.834	15.64	5.896
190	16.54	6.153	16.51	6.211
200	17.39	6.469	17.37	6.526
210	18.23	6.784	18.22	6.838
220	19.07	7.095	19.07	7.147
230	19.90	7.404	19.90	7.454
240	20.73	7.712	20.73	7.759
250	21.55	8.018	21.55	8.064
260	22.36	8.322	22.36	8.366
270	23.17	8.622	23.18	8.665
273.15	23.42	8.716	23.44	8.758
280	23.97	8.918	23.98	8.960
290	24.75	9.212	24.77	9.252
298.15	25.39	9.449	25.41	9.488
300	25.53	9.502	25.55	9.541
320	27.07	10.07	27.09	10.11
340	28.58	10.64	28.60	10.67
360	30.06	11.19	30.08	11.22
380	31.51	11.73	31.53	11.76
400	32.92	12.26	32.94	12.29
420	34.31	12.78	34.33	12.80
440	35.67	13.28	35.69	13.31
460	37.00	13.78	37.02	13.80
480	38.32	14.27	38.32	14.30
500	39.61	14.76	39.61	14.78
550	42.74	15.93	42.74	15.95
600	45.75	17.05	45.75	17.07
650	48.64	18.13	48.64	18.15
700	51.43	19.18	51.43	19.20
750	54.14	20.19	54.14	20.21
800	56.77	21.18	56.78	21.19
850	59.34	22.14	59.34	22.15
900	61.84	23.07	61.84	23.08
950	64.28	23.98	64.28	24.00

TABLE 8. The viscosity and thermal conductivity of krypton — Continued

b) Negligible contribution of initial density dependence up to 0.101325 MPa

Temperature (K)	Viscosity (μPa s)	Therm. cond. (mW/m K)
1000	66.66	24.88
1050	69.00	25.75
1100	71.29	26.61
1150	73.55	27.45
1200	75.76	28.28
1250	77.94	29.09
1300	80.08	29.89
1350	82.20	30.68
1400	84.28	31.46
1450	86.34	32.23
1500	88.36	32.99
1550	90.37	33.74
1600	92.35	34.48
1650	94.31	35.21
1700	96.25	35.94
1750	98.17	36.65
1800	100.1	37.36
1850	101.9	38.06
1900	103.8	38.76
1950	105.7	39.45
2000	107.5	40.13
2050	109.3	40.81
2100	111.1	41.48
2150	112.9	42.15
2200	114.7	42.81
2250	116.4	43.47
2300	118.2	44.12
2350	119.9	44.77
2400	121.6	45.41
2450	123.3	46.05
2500	125.0	46.68
2600	128.4	47.94
2700	131.7	49.18
2800	135.0	50.41
2900	138.3	51.62
3000	141.5	52.82
3100	144.7	54.01
3200	147.8	55.19
3300	150.9	56.35
3400	154.0	57.51
3500	157.1	58.65
3600	160.1	59.79
3700	163.2	60.91
3800	166.1	62.03
3900	169.1	63.13
4000	172.1	64.23
4100	175.0	65.32
4200	177.9	66.41
4300	180.8	67.48
4400	183.6	68.55
4500	186.5	69.62
4600	189.3	70.67
4700	192.1	71.72
4800	194.9	72.76
4900	197.7	73.80
5000	200.5	74.83

TABLE 9. The viscosity and thermal conductivity of xenon

a) With contribution of initial density dependence

	Zero-density values		Values at 0.101325 MPa	
Temp. (K)	Viscosity (μPa s)	Therm. cond. (mW/m K)	Viscosity (μPa s)	Therm. cond. (mW/m K)
165.03	13.03	3.094	12.72	3.155
170	13.40	3.182	13.13	3.242
180	14.15	3.361	13.94	3.419
190	14.90	3.539	14.73	3.595
200	15.65	3.717	15.51	3.771
210	16.41	3.898	16.30	3.950
220	17.18	4.080	17.09	4.130
230	17.94	4.260	17.87	4.309
240	18.69	4.439	18.64	4.485
250	19.45	4.620	19.41	4.665
260	20.21	4.801	20.18	4.844
270	20.97	4.981	20.95	5.023
273.15	21.21	5.037	21.19	5.079
280	21.73	5.160	21.70	5.202
290	22.48	5.339	22.48	5.379
298.15	23.09	5.483	23.09	5.522
300	23.23	5.516	23.23	5.555
320	24.71	5.867	24.70	5.904
340	26.17	6.216	26.17	6.250
360	27.63	6.563	27.63	6.596
380	29.06	6.904	29.08	6.935
400	30.47	7.237	30.49	7.267
420	31.86	7.567	31.88	7.596
440	33.23	7.893	33.25	7.921
460	34.58	8.215	34.60	8.242
480	35.91	8.533	35.94	8.559
500	37.23	8.846	37.25	8.871
550	40.42	9.608	40.45	9.630
600	43.51	10.34	43.53	10.36
650	46.48	11.05	46.48	11.07
700	49.37	11.74	49.37	11.76
750	52.17	12.41	52.17	12.42
800	54.89	13.06	54.89	13.07
850	57.53	13.69	57.53	13.70
900	60.10	14.30	60.10	14.32
950	62.61	14.90	62.61	14.91
1000	65.06	15.49	65.06	15.50
1050	67.46	16.06	67.46	16.07
1100	69.81	16.62	69.81	16.63
1150	72.12	17.17	72.12	17.18
1200	74.38	17.71	74.38	17.72
1250	76.60	18.24	76.60	18.25

TABLE 9. The viscosity and thermal conductivity of xenon — Continued

b) Negligible contribution of initial density dependence up to 0.101325 MPa

Temperature (K)	Viscosity (μPa s)	Therm. cond. (mW/m K)
1300	78.79	18.76
1350	80.94	19.28
1400	83.06	19.78
1450	85.15	20.28
1500	87.21	20.77
1550	89.24	21.26
1600	91.24	21.74
1650	93.22	22.21
1700	95.18	22.68
1750	97.12	23.14
1800	99.03	23.60
1850	100.9	24.05
1900	102.8	24.49
1950	104.7	24.94
2000	106.5	25.38
2050	108.3	25.81
2100	110.1	26.24
2150	111.9	26.67
2200	113.7	27.09
2250	115.5	27.51
2300	117.2	27.93
2350	118.9	28.34
2400	120.7	28.76
2450	122.4	29.16
2500	124.1	29.57
2600	127.4	30.37
2700	130.8	31.16
2800	134.0	31.94
2900	137.3	32.71
3000	140.5	33.48
3100	143.7	34.23
3200	146.8	34.98
3300	149.9	35.72
3400	153.0	36.45
3500	156.0	37.18
3600	159.0	37.90
3700	162.0	38.61
3800	165.0	39.32
3900	167.9	40.02
4000	170.9	40.72
4100	173.8	41.41
4200	176.6	42.09
4300	179.5	42.77
4400	182.3	43.45
4500	185.2	44.12
4600	188.0	44.79
4700	190.8	45.45
4800	193.5	46.11
4900	196.3	46.77
5000	199.0	47.42

5. Tabulations

The scheme described in the first two sections has been employed to generate recommended values for the viscosity and the thermal conductivity of the monatomic gases from their normal boiling point up to 5000 K and for zero density as well as 0.101325 MPa. At a certain temperature the contribution of the initial density dependence vanishes. Therefore, the tables for higher temperatures contain only one column for viscosity and thermal conductivity, respectively.

Table 4 gives a survey of relative uncertainties for the five gases.

The recommended values are listed in Tables 5–9. The temperatures have been chosen in a way that enables the values at intermediate temperatures to be calculated by linear interpolation without any loss of accuracy.

6. Conclusions

Tables of accurate and reliable data for the viscosity and thermal conductivity of the five monatomic gases, based upon a limited set of accurate experimental data and the kinetic theory, has been presented. For each gas the uncertainty of the recommended values is detailed. From a comparison of the proposed data at zero density and at 0.101325 MPa the importance of the initial density dependence especially at low temperatures becomes obvious.

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