# 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

## E. Bich, J. Millat, and E. Vogel

*Universität Rostock, Fachbereich Chemie, Buchbinderstrasse 9, D-O-2500 Rostock 1, Federal Republic of Germany.*

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.

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

and

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

Here, $T^* = kT/\epsilon$, $\epsilon/k$ represents the potential well depth, $\sigma$ 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]

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

and

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

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

$$\eta(\rho,T) = \eta_0(T) + \eta_1(\rho,T) + ... =$$
$$\eta_0(1 + B_\eta \ \rho + ...) \qquad (7)$$

and

$$\lambda(\rho,T) = \lambda_0(T) + \lambda_1(\rho,T) + ... =$$
$$\lambda_0(1 + B_\lambda \ \rho + ...). \qquad (8)$$

The so-called 2nd viscosity and thermal conductivity virial coefficients $B_\eta$ and $B_\lambda$ consist of three contributions:

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

$B_{\eta,\lambda}^{(2)}$ 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

$$\theta = \epsilon_{M-D}/\epsilon_M \qquad (10a)$$

and that of length scales

$$\delta = \sigma_{M-D}/\sigma_M \qquad (10b)$$

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

$$\theta = 1.15 \qquad ; \qquad \delta = 1.02 . \qquad (11)$$

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

$$\theta = 1.25 \text{ and } \delta = 1.04 \qquad (12)$$

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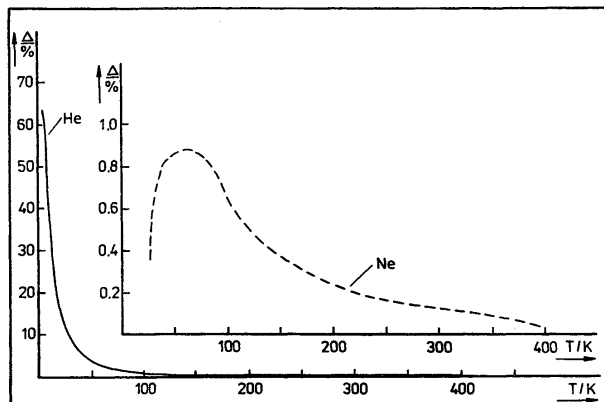
FIG. 1. Relative contribution of quantum effects to the zero-density
viscosity of helium and neon.

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 $B^{(2)}$ and $B^{(3)}$ be-
low $T^* = 1.0$ 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 ini-
tial density dependence of $\lambda$ should be negative. The ex-
perimental results of Acton and Kellner[34] as well as
those of Roder[35] on the other hand show positive values
for $B_\lambda$. 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 depen-
dence 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 negli-
gible. 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 $\eta$
in the temperature range 20–100 K. Between 5 and 20 K
only zero-density values including the quantum correc-
tion 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 discrepan-
cies 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 avail-
able literature. Therefore, we have employed two com-
plementary 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: oscil-
lating-disc viscometers or capillary viscometers, if a com-
plete 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 compari-
son of experimental data with results calculated from in-
teratomic potentials and an extended law of
corresponding states analysis. Thus, we have commenced
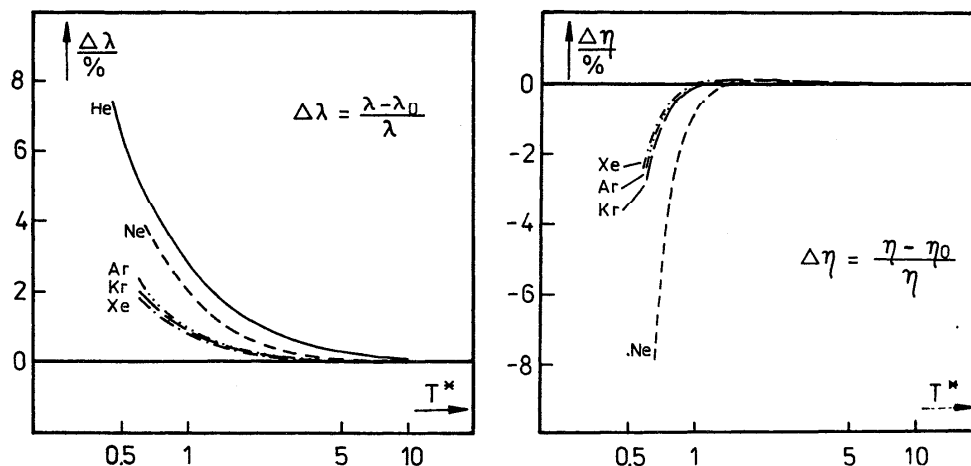


FIG. 2. Relative contribution of the initial density dependence to the viscosity and thermal conductivity of
monatomic gases.

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 $\epsilon/k$ and $\sigma$ which are not identical with the potential parameters $\epsilon/k$ and $\sigma$ 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 $\epsilon/k$ and $\sigma$ obtained by fitting Eq. (14) to experimental zero-density transport coefficients $\eta_0$ and $\lambda_0$ are given in Table 3.

Consistent data for $\eta_0$ and $\lambda_0$ 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].



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

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 | $\epsilon/k$ (K) | $\sigma$ (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 |
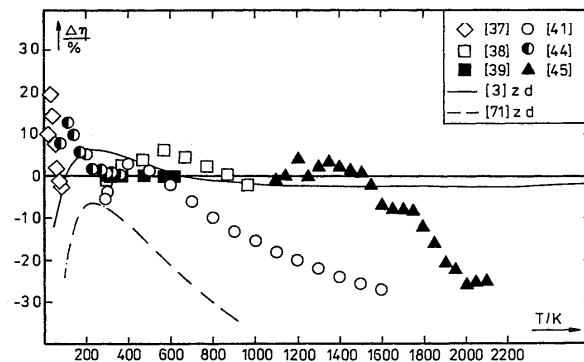


FIG. 4. Comparison of recommended viscosity values of neon to experimental results and earlier correlations.

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 |
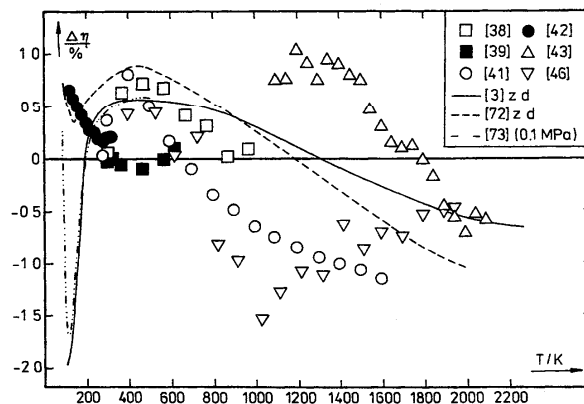


FIG. 5. Comparison of recommended viscosity values of argon to experimental results and earlier correlations.

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.
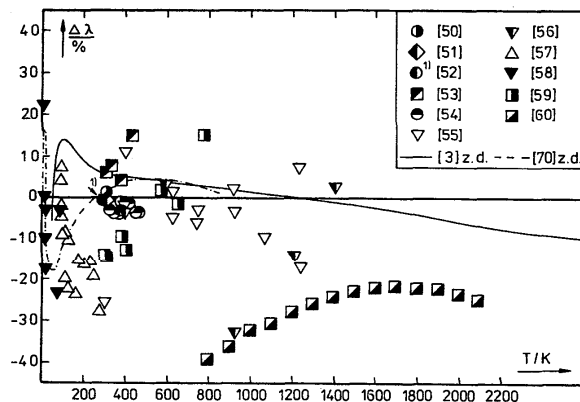


FIG. 9. Comparison of recommended thermal conductivity values of helium to experimental data and earlier correlations — up to 2100 K.
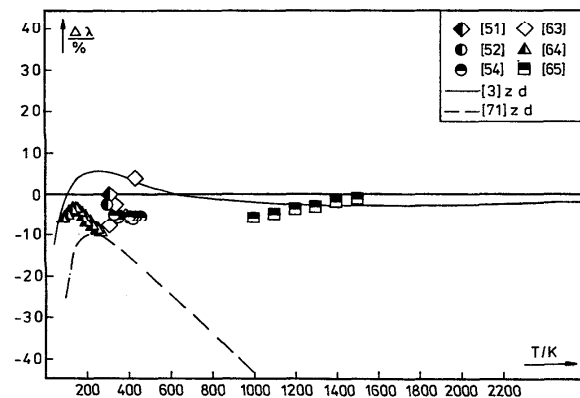


FIG. 10. Comparison of recommended thermal conductivity values of neon to experimental data and earlier correlations.
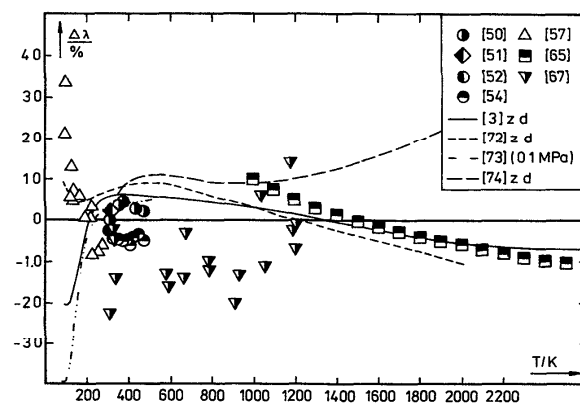


FIG. 11. Comparison of recommended thermal conductivity values of argon to experimental data and earlier correlations.
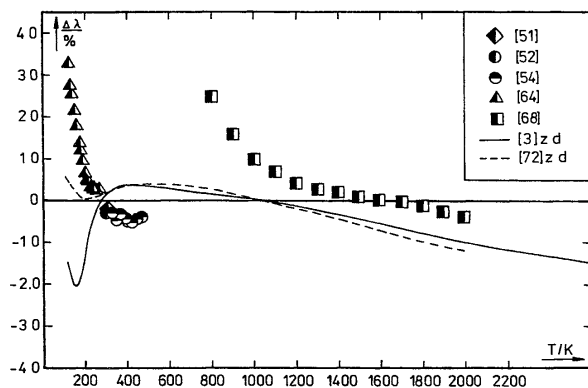
FIG. 12. Comparison of recommended thermal conductivity values of krypton to experimental data and earlier correlations.



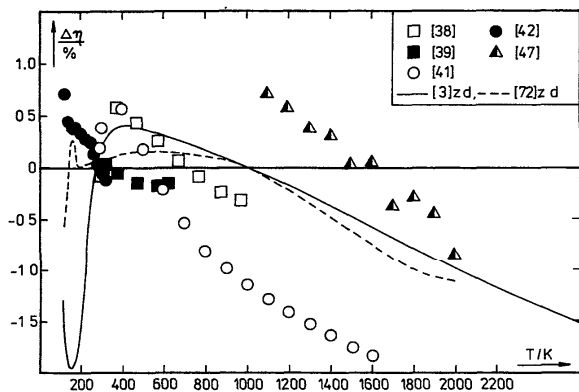FIG. 13. Comparison of recommended thermal conductivity values of xenon to experimental data and earlier correlations.
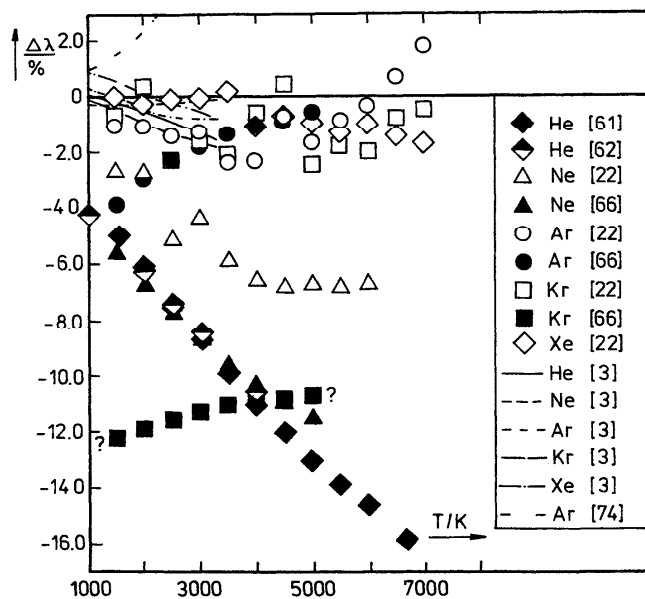


FIG. 14. Comparison of recommended high temperature thermal conductivities of monatomic gases to results of shock tube measurements and earlier correlations.



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 ($\mu$Pa s) | Therm. cond. (mW/m K) | Viscosity ($\mu$Pa 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

| Temperature (K) | Zero-density values | | Values at 0.101325 MPa | |
|---|---|---|---|---|
| | 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) | Therm. cond. (mW/m K) | Values at 0.101325 MPa Viscosity (μPa s) | 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. | Zero-density values | | Values at 0.101325 MPa | |
|---|---|---|---|---|
| | Viscosity | Therm. cond. | Viscosity | Therm. cond. |
| (K) | ($\mu$Pa s) | (mW/m K) | ($\mu$Pa s) | (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 ($\mu$Pa 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

| Temp. (K) | Zero-density values | | Values at 0.101325 MPa | |
|---|---|---|---|---|
| | 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**

| Temp. (K) | Zero-density values Viscosity (μPa s) | Therm. cond. (mW/m K) | Values at 0.101325 MPa 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.

## 7. Acknowledgements

## 8. References

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