

Viscosity and Thermal Conductivity of Dry Air in the Gaseous Phase

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In view of the importance of air in science and technology and the abundance of experimental data, we present in this report a consistent set of critically evaluated data and an up-to-date correlation of the viscosity and the thermal conductivity of air in the gaseous phase over a wide range of temperature and pressure. This is especially important for the viscosity, since the recent data show systematic differences compared with the old standard value used for many years. The present paper was written in order to document the critical evaluation of the latest data sets and to present a new set of correlations of the viscosity and the thermal conductivity of air. The range covered is from 85 to 2000 K for temperature and up to 100 MPa for pressure.

Key words: air; high pressure; high temperature; low temperature; thermal conductivity; transport properties; viscosity.

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Nomenclature

B	= second virial coefficient in m^3/mol
B^*	= $20.5 \times 10^{-6} \text{ m}^3/\text{mol}$
C	= third virial coefficient in m^6/mol^2
P	= pressure in MPa
T	= absolute temperature in terms of IPTS-68 in K
T^*	= 132.5 K
T_r	= T/T^*
T_B	= Boyle temperature in K (340 K)
Z	= compressibility factor
η	= viscosity in $10^{-6} \text{ Pa}\cdot\text{s}$
λ	= thermal conductivity in $10^{-3} \text{ W}/(\text{m}\cdot\text{K})$
ρ	= density in kg/m^3
$\bar{\rho}$	= molar density in mol/m^3
ρ^*	= $314.3 \text{ kg}/\text{m}^3$
ρ_r	= ρ/ρ^*
τ	= T/T_B

1. Introduction

Air is undoubtedly one of the most important substances in every aspect of human activity. Industrial applications of air require a consistent set of reliable data on its thermophysical properties. Among important properties of air, an evaluation of the data is particularly needed for the viscosity, since the latest data show a considerable systematic deviation from the correlations once used as standard. For the thermal conductivity, a new evaluation is needed since extensive experimental data have been published in comparatively recent years.

The present study was intended to make a critical evaluation of the latest data of the viscosity and the thermal conductivity of air and to present a consistent set of correlations for these properties over a wide range of temperature and pressure.

Although the available experimental data on the viscosity and the thermal conductivity of air are abundant, most of the older data are concentrated in a narrow region around room temperature and atmospheric pressure. In the present study, experimental data published prior to 1960 were screened on the basis of other credible review papers. Screened data prior to 1960 and all the data after that year were taken into account in the evaluation process. These data were analyzed in every respect and the reference data for the present formulation were selected. The liquid region was excluded from the correlation due to the lack of reliable

experimental data. In the high-temperature region where experimental data are limited, theoretical estimations were introduced in order to make it possible to extrapolate the present formulation to higher temperatures and pressures.

In order to correlate an equation for the viscosity or the thermal conductivity over a wide range of temperature and pressure, temperature and density are commonly used as independent variables. Therefore, a survey and an evaluation of the available equations of state for air was undertaken in the course of the present study.

2. Preliminary Considerations

2.1. Density Sources

Since the present formulation employs temperature and density as the independent variables, the density sources are needed in correlating equations as well as in using them. Although the experimental uncertainty in density determination is normally much smaller than that in viscosity or thermal conductivity, the effect of the former might not be negligible.

The effect of the difference of the density sources was analyzed in two stages. Namely, in Sec. 2.1, a critical comparison of available equations of state was done and the difference among them was quantitatively shown. Then, the effect of that amount of difference on the viscosity and the thermal conductivity was analyzed in Sec. 2.2.

After an extensive survey and a detailed comparison, four equations of state, namely, the equations of Baehr and Schwiier (1961),¹ of Vasserman, Kazavchinskii, and Rabinovich (1966),² of Vukalovich, Zubarev, Aleksandrov, and Kozlov (1974),^{3,a} and of Vasserman, Golovskii, Kreizerova, and Tsymarnyi (1977),⁴ were selected and taken into consideration. Although the widest range of validity is claimed for the equation of Baehr *et al.* (1961),¹ this equation had been correlated before experimental PvT data of Vukalovich³ exceeding 200 °C (473 K) became available. This was also the situation with respect to the first equation of Vasserman *et al.* (1966).² At higher temperatures, both equations are based on estimated values, while Vukalovich *et al.*³ based the correlation of their equation of state on their own experimental PvT data up to 600 °C (873 K). The second equation of Vasserman *et al.*⁴ is valid in the lower temperature region, too. Among the four equations of state, that of Vukalovich *et al.* (1974)³ and the second equation of Vasserman *et al.* (1977)⁴ agree with each other within 0.12% for the density.

At temperatures around 300 K, the densities calculated with the four equations agree well with each other. However, with increasing temperature, the differences among the calculated densities become larger. For example, deviation from Vukalovich's equation (1974)³ are: -1.5% at 800 K and 100 MPa for Baehr's equation (1961)¹ and -2.7% at 1200 K and 100 MPa for Vasserman's (1966).³

As mentioned later, the present equations for the viscosity and for the thermal conductivity are intended for temperatures up to 2000 K and for pressures up to 100 MPa. None of the equations of state mentioned above can cover the entire range. Therefore, the present authors developed the following virial equation of state to cover the high-temperature region:

$$Z = 1 + B(\tau)\bar{\rho} + C(\tau)\bar{\rho}^2, \quad (1)$$

where

$$B(\tau) = B^* \sum_{i=-4}^1 b_i \tau^i, \quad (1a)$$

$$C(\tau) = B^{*2} \sum_{i=-3}^0 c_i \tau^i, \quad (1b)$$

and

$$\tau = T/T_B. \quad (1c)$$

The constants for Eq. (1) are given in Table 1. The equations of the virial coefficients $B(\tau)$ and $C(\tau)$ were determined considering the experimental PvT data for several other gases, the theoretical prediction of $B(\tau)$ and $C(\tau)$ by means of the 12-6 potential,⁵ and the values of T_B and B^* determined from the PvT data for air of Vukalovich *et al.* (1974).³ Equation (1) can be used at temperatures from 300 to 2000 K, if necessary, and it is presumed that the pressure limit of Eq. (1) is higher than 100 MPa at temperatures above 1000 K. Equation (1) gives a density value greater only by 0.3% than the equation of state of Vukalovich *et al.* (1974)³ at 1200 K and at 100 MPa.

^aThe report on the equation of state in Ref. 3 has the following typographical errors: (S_1, S_2, S_3, S_4) should read (4, 4, 3, 3) and b_{42} should read -47.463 328.

Table 1. Constants in Eq. (1)

T_B	340 (K)	c_{-3}	2.5028 7
B^*	$20.5 (10^{-6} \text{ m}^3/\text{mol})$	c_{-2}	-5.5210 9
		c_{-1}	4.2963 1
b_{-4}	-0.0016 8785	c_0	1.1966 5
b_{-3}	-0.0223 299		
b_{-2}	-0.1704 00		
b_{-1}	-1.9478 3		
b_0	2.1605 9		
b_1	-0.0222 430		

Throughout the present study, the density was calculated with Vasserman's second equation of state⁴ at temperatures below 273 K, with Vukalovich's³ in the temperature range 273–1273 K and with Eq. (1) at temperatures above 1273 K.

2.2. Effect of the Density Difference

Some types of commonly-used viscometers actually measure the kinematic viscosity, and the translation of the experimental result into the dynamic viscosity requires a

 Table 2. Effect of a one percent increase in density on the viscosity and the thermal conductivity (%)^a

P (MPa)	T (K)							
	85	140	200	300	500	1000	1500	2000
0.01	0.0006	0.0002	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000
	0.0017	0.0006	0.0003	0.0001	0.0001	0.0000	0.0000	0.0000
0.1	0.0069	0.0025	0.0012	0.0006	0.0002	0.0001	0.0000	0.0000
	0.018	0.0064	0.0032	0.0015	0.0006	0.0002	0.0001	0.0000
1.0		0.036	0.016	0.0068	0.0026	0.0008	0.0004	0.0002
		0.073	0.034	0.016	0.0060	0.0017	0.0008	0.0005
5.0			0.15	0.053	0.018	0.0046	0.0022	0.0013
			0.21	0.089	0.033	0.0091	0.0043	0.0026
10.0			0.42	0.14	0.044	0.011	0.0050	0.0029
			0.50	0.19	0.070	0.019	0.0090	0.0053
20.0			1.0	0.35	0.11	0.027	0.012	0.0069
			1.0	0.41	0.15	0.041	0.019	0.011
30.0			1.4	0.57	0.19	0.047	0.021	0.012
			1.4	0.63	0.23	0.065	0.030	0.017
40.0				0.78	0.27	0.068	0.030	0.017
				0.82	0.32	0.089	0.041	0.024
60.0				1.2	0.44	0.11	0.052	0.029
				1.1	0.48	0.14	0.065	0.037
80.0				1.4	0.61	0.16	0.075	0.043
				1.3	0.64	0.19	0.089	0.051
100.0				1.7	0.78	0.22	0.10	0.057
				1.5	0.79	0.24	0.11	0.066

^a Of each pair of figures, the upper represents the change in the viscosity and the lower that in the thermal conductivity.

knowledge on the density value. However, fortunately, all the experimental viscosity data of air were reported in the region where the discrepancy among the density sources is not significant and the effect introduced to experimental viscosity data is estimated about 0.2% at most (at 400 K and 30 MPa), which is within the experimental uncertainty. A recalculation of experimental viscosity data on the common density source was not, therefore, performed.

The effect of the density differences on the calculated viscosity and the thermal conductivity with the present formulations can be estimated by calculating the derivatives $(\partial\eta/\partial\rho)_T$ and $(\partial\lambda/\partial\rho)_T$ from the new equations described later. Table 2 gives the deviation of the viscosity and the thermal conductivity resulted from a change in density by 1%. The effect of the different density sources on calculated viscosity and thermal conductivity values, obtained by multiplying the entry in Table 2 with the actual difference of calculated density among the four equations of state, is at most 0.7% at 673 K and 100 MPa, and is negligible in other regions.

2.3. Effect of the Fluctuation of the Composition of Air

According to *U. S. Standard Atmosphere 1976*,⁶ the composition of dry air is regarded as constant at a height up to about 86 km. The fractions of ten major components of dry air are given in Table 3. Among the ten components, those except N₂, O₂, Ar and CO₂ are present in traces and can be neglected in practical calculations.

Air contains also considerable amounts of water vapor in many cases. Since the fluctuation of the water vapor content is large, all the investigators had desiccated the sample air before measuring the viscosity or the thermal conductivity.

The fraction of CO₂ in atmospheric air also fluctuates due to vegetation and human activities, although the vari-

ation is smaller. Some experimentalists performed measurements with CO₂-free air. Therefore, the effect of the difference in the CO₂ content on the viscosity and thermal conductivity of air must be estimated. The difference of these properties between CO₂-free air and ordinary dry air was calculated using the mixing rules for the viscosity and for the thermal conductivity.⁷⁻¹⁸ The result suggests that the difference cannot be more than 0.04% for both properties for any experimental data, which is much smaller than the experimental uncertainty. Therefore no correction for the CO₂ content was required.

2.4. Effect of the Different Temperature Scales

In 1968, the new International Practical Temperature Scale (IPTS-68) was adopted and the former temperature scale (IPTS-48) became obsolete. Therefore the effect of the difference of the two temperature scales was estimated using the preliminary correlation.

Although the difference between IPTS-48 and IPTS-68 is very small at room temperature (for example, 0.009 K at 300 K), it becomes larger with increasing temperature. However, as shown in Table 4, the effect of a difference in temperature on an evaluation of the viscosity and the thermal conductivity of dilute air is small enough at temperatures below 1000 K. Above 1000 K, larger tolerance assigned at high temperature in the present correlations makes tolerable larger uncertainty due to the temperature scale. No correction has, therefore, been applied.

Table 4. Effect of the difference between IPTS-48 and IPTS-68 on the viscosity and the thermal conductivity of air at low pressure

T (K)	T48-T68 (K)	$\Delta\eta_0$ (%)	$\Delta\lambda_0$ (%)
90	-0.013	-0.015	-0.013
100	-0.009	-0.0089	-0.0095
200	-0.034	-0.015	-0.016
300	0.008	0.0021	0.0023
400	-0.010	-0.0018	-0.0020
500	-0.053	-0.0075	-0.0083
600	-0.076	-0.0087	-0.0097
700	-0.075	-0.0073	-0.0082
800	-0.088	-0.0073	-0.0084
900	-0.195	-0.014	-0.017
1000	-0.46	-0.030	-0.035
1100	-0.74	-0.044	-0.052
1200	-1.03	-0.056	-0.067
1300	-1.31	-0.065	-0.079
1400	-1.6	-0.074	-0.091
1500	-1.7	-0.073	-0.091
1600	-1.9	-0.076	-0.096
1700	-2.1	-0.079	-0.10
1800	-2.3	-0.082	-0.10
1900	-2.5	-0.084	-0.11
2000	-2.7	-0.086	-0.11

Table 3. Molecular weights and assumed composition of sea-level dry air

Gas species	Molecular weight (kg/kmol)	Volume fraction
N ₂	28.0314	0.78084
O ₂	31.9988	0.209476
Ar	39.948	0.00934
CO ₂	44.00995	0.000314
Ne	20.183	0.00001818
He	4.0026	0.00000524
Kr	83.80	0.00000114
Xe	131.30	0.000000087
CH ₄	16.04303	0.000002
H ₂	2.01594	0.0000005
Dry air	28.9644	

2.5. Effect of the Different Calibration Standards

Some experimental studies were carried out on a relative basis and the results were affected by the uncertainty in the calibration standards.

In the case of the viscosity, many measurements, especially by the capillary method, were done on a relative basis. For gases, no commonly-accepted calibration standard for the viscosity exists (for the viscosity of liquids, the viscosity of water at 293.15 K and at 1 atm is commonly used). Nitrogen, air, helium, and other gases were used as the calibrating gases. Among studies which were considered important in the present study, Matthews, Thomas, Dufty, and Smith (1976)^{V50} used a capillary viscometer. They calibrated their capillary with the viscosity of nitrogen at 293.2 K,

$$\eta = 17.57 \times 10^{-6} \text{ Pa}\cdot\text{s} \text{ (Ref. R7)}$$

which differs by about 0.1% from the latest precise measurement of Kurase, Kobayashi, and Kawata (1976).¹⁹ The measurement of Latto *et al.*^{V48} was on an absolute basis.

In the case of the oscillating-disk method, the edge correction factor has to be determined experimentally. Kestin and Leidenfrost (1959),^{V43} Hellemans, Kestin, and Ro (1973)^{V47} and Timrot, Serednitskaya, and Traktueva (1975)^{V49} used nitrogen, air, helium, etc., in order to determine the edge correction factor. The uncertainty in the edge correction factor does not seriously affect the resulting viscosity data.

To sum up, the effect of different calibration standards, at least in the studies considered important in the present study, is not significant.

In the case of the thermal conductivity, all of the important studies were carried out on an absolute basis.

2.6. Conversion into SI

In the present study, all the data were converted into SI. In the case of the thermal conductivity, several different definitions for the unit "calorie" exist and it is often unclear which calorie was used. The definition for the "cal₁₅" (1 cal₁₅ = 4.1855 J) was adopted in this study. The difference between cal₁₅ and calories of other definitions is at most 0.1%, which is smaller than the experimental uncertainty of the thermal conductivity of air by an adequate margin.

2.7. Extrapolation of the Experimental Viscosity and Thermal Conductivity to Zero Pressure

In this study, as mentioned later, the viscosity and the thermal conductivity of air were correlated as the sums of the quantities at zero pressure (which can be obtained by extrapolating data at low pressures to zero pressure limit) and the excess quantities (the increase of the property value from that at zero pressure limit). Fortunately, at room temperature and higher, the pressure dependence of the viscosity and the thermal conductivity of air is very small. Therefore, experimental data at one or several atmospheres can be treated as data at zero pressure with no corrections. However, at cryogenic temperatures, the pressure dependence of the viscosity and the thermal conductivity becomes noticeable. For example, at 90 K, the viscosity of air at 1 atm is larger than that at zero pressure by 0.6%, according to the present correlation. For the thermal conductivity, this difference may increase to 1.6%. Therefore, adjustment for this difference was taken into account in the course of correlation.

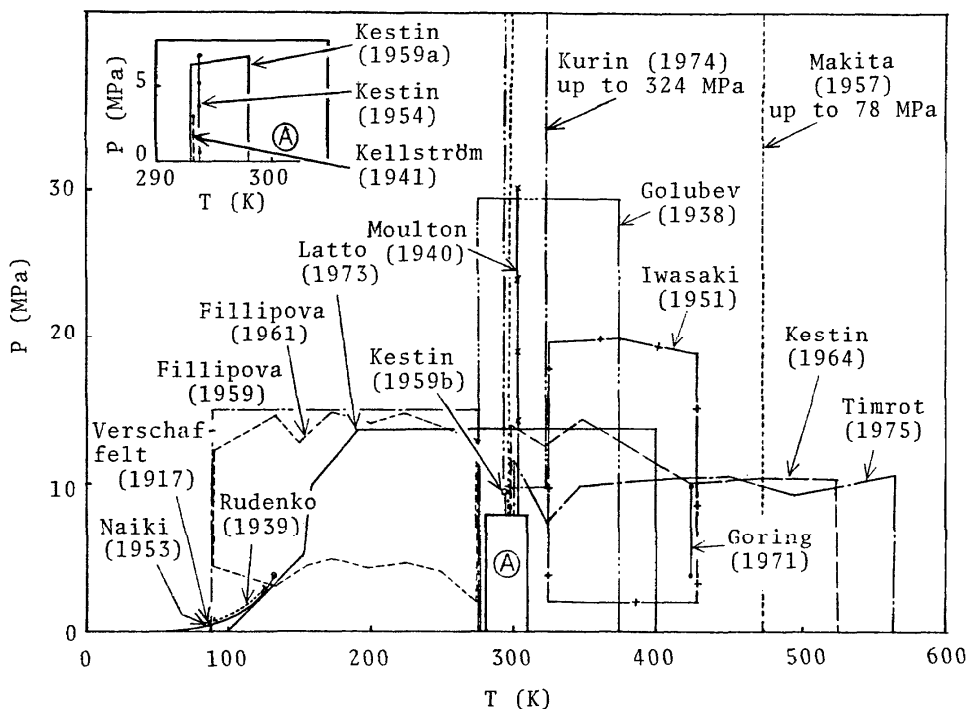


FIG. 1. Regions of experimental data on the viscosity of air at high pressure.

3. Viscosity

3.1. General Remarks

Most of the experimental viscosity data for air were obtained by the capillary or the oscillating-disk method. A large number of data are available over the temperature range 80–1850 K at atmospheric or low pressures and a number of measurements at high pressures were published since 1930's (Refs. V1–V58). Some data are available for liquid air (Refs. V41, V53, V56–V58). The ranges of the experimental studies at high pressures are shown in Fig. 1.

Also, a number of reviews and surveys of experimental data of the viscosity of air are available (Refs. 2, R1–R11). However, the recommended values or equations in these reviews are often not based on the latest data and the temperature and pressure ranges are not sufficiently wide in most cases.

Since the reports on the measurement of the viscosity of air at atmospheric pressure are very large in number, only important studies have been selected through screening on the basis of reliable reviews. Reviews by the Thermophysical Properties Research Center (TPRC) (1975),^{R6} by Maitland and Smith (1972),^{R7} and by Watson (1972)^{R8} were consulted. Selected reports before 1960 and all the reports after 1960 were taken into account in this study.

The most serious problem concerning the viscosity of dilute air is that at high temperature the important experimental data naturally divide themselves into two sets, which systematically differ from each other. The older set, typically represented by the data of Trautz and co-workers (1925, 1926, 1929, 1930, and 1931)^{V11, V12, V15–V17}, had been considered as a reference standard for many years. The other and recent set, represented by the data of Kestin and co-workers (1964, 1968, and 1973)^{V45–V47} and Matthews and co-workers (1976),^{V50} shows a higher trend at high temperatures.

As for experimental viscosity data at high pressures, old data show excessive scatter and seem to be unreliable. The liquid region has been excluded from the present correlation since the present status for this region is not ripe to make a reliable correlation.

3.2. Selection of Data

First, we will consider the data at atmospheric or low pressures. Although the temperature range of available experimental data at atmospheric or low pressures is wide (80–1850 K), most data concentrate around room temperature. The data at temperatures above 1000 K, as well as those at cryogenic temperatures, are scarce.

At room temperature (around 300 K), six sets of data, namely, those of Iwasaki and Kestin (1963),^{V44} of Kestin and Whitelaw (1964),^{V45} of DiPippo and Kestin (1968),^{V46} of Hellemans, Kestin, and Ro (1972),^{V47} of Latto and Saunders (1973),^{V48} of Timrot, Serednitskaya, and Traktueva (1975),^{V49} and of Matthews, Thomas, Dufty, and Smith (1976)^{V50} were reported after 1960. After a careful evaluation, all of these data were judged to be reliable and were, therefore, selected as the basis of the present correlation. From the data published before 1960, two sets of data of

Kestin and Leidenfrost (1959)^{V42, V43} were also included.

For the high-temperature region, five sets of recent data were reported after 1960 at temperatures above 500 K, namely, those of Kestin *et al.* (1964),^{V45} of DiPippo *et al.* (1968),^{V46} of Hellemans *et al.* (1972),^{V47} of Timrot *et al.* (1975),^{V49} and of Matthews *et al.* (1976).^{V50} At temperatures above 1000 K, only the data of Matthews *et al.*,^{V50} up to 1620 K, are available. Trautz and Zink (1930)^{V16} and Vasilescu (1945)^{V36} also reported viscosity data at temperatures above 1000 K, but these older data are systematically lower than the recent data at temperatures above 400 K. The deviation increases with increasing temperature and reaches about 7% at 1600 K, as shown later in Fig. 4. Similar disagreement has been observed also for other gases.^{R7} In the case of these older studies, the presence of an error in temperature measurement was suspected in Ref. 20. Therefore, in the high-temperature region, five sets of data after 1963 were selected as the reference data.

In the low-temperature region, two sets of data were reported after 1960, namely, those of Latto *et al.* (1973)^{V48} down to 100 K and of Matthews *et al.* (1976)^{V50} down to 120 K. The mutual agreement of the two sets of data is satisfactory and a close check of the reports indicated that these data were reasonably reliable. Also the data of Johnston and McCloskey (1940)^{V32} were consulted with smaller assigned weight, so as to cover the lowest temperature where neither the data of Latto *et al.*^{V48} nor those of Matthews *et al.*^{V50} were available. Therefore, three sets of data were used as the basis of correlation in the low-temperature region.

The reference data at atmospheric pressure are seen listed in Table 5.

At temperatures above 1620 K, no reliable experimental data are available. But demand for high-temperature data is very strong and, on the other hand, experience with other gases suggests the applicability of a simple excess viscosity–density relation to higher temperatures. Therefore, in the temperature range 1620–2000 K, the viscosity of dilute air was estimated using mixing rules for the gas viscosity,^{7–14} on the assumption that air is a mixture of N₂, O₂, Ar, and CO₂. The viscosity and the intermolecular potential parameters for N₂, O₂, Ar, and CO₂ were taken from a recent study by the present authors.⁵ Mutual agreement of viscosity values

Table 5. Selected sources on the viscosity of air at atmospheric pressure

First author	Year	Method	Temperature (K)	Ref.
Johnston*	1940	Oscill. disk	90 - 300	V32
Kestin	1959a	Oscill. disk	293 - 298	V42
Kestin	1959b	Oscill. disk	293	V43
Iwasaki	1963	Oscill. disk	293	V44
Kestin	1964	Oscill. disk	298 - 523	V45
DiPippo	1968	Oscill. disk	298 - 773	V46
Hellemans	1973	Oscill. disk	298 - 873	V47
Latto	1973	Capillary	100 - 400	V48
Timrot	1975	Oscill. disk	295 - 570	V49
Matthews	1976	Capillary	120 - 1620	V50

* See text.

obtained by different mixing rules was excellent and at temperatures below 1620 K, the calculated values agreed very well with the reference experimental data. The estimated viscosity thus obtained was also taken into account in the present correlation.

An analysis of the available data for dense gaseous air suggests that the excess viscosity (the departure of the viscosity at high pressure from that at the same temperature but at sufficiently low pressure) shows no obvious temperature dependence and therefore it can be expressed as a function of density alone in a manner similar to that applicable to simple pure gases. With this assumption, the data obtained at different temperatures can be compared with each other on the basis of their excess viscosity.

In the case of the viscosity of air in the dense gaseous region, the scatter observed in the data before 1960 seems excessive, except for the two sets of data due to Kestin *et al.*^{V42,V43} Therefore, experimental data after 1960 were surveyed and critically evaluated. Six sets of experimental data have been reported for the viscosity of dense gaseous air since 1960, namely, those of Filippova and Ishkin (1961),^{V53} of Kestin *et al.* (1964),^{V45} of Goring and Eagan (1971),^{V54} of Latto *et al.* (1973),^{V48} of Kurin and Golubev (1974),^{V55} and of Timrot *et al.* (1975).^{V49} Although the pressure range of the data of Kurin *et al.* (1974)^{V55} reaches 324 MPa, other studies end at 15 MPa. As for the temperature range, the data of Filippova *et al.* (1961)^{V53} are available down to the critical temperature and the temperature range of the data of Timrot *et al.* (1975)^{V49} extend to 566 K. Most of the data were, however, obtained around room temperature. In terms of density, the data of Kurin *et al.*^{V55} and those of Filippova *et al.*^{V53} reach about 900 kg/m³ and 650 kg/m³, respectively. Except for these two sets of data, the maximum density is confined to about 400 kg/m³.

The data of Filippova *et al.*^{V53} giving the kinematic viscosity have excessive scatter and show quite different density dependence from that of the data of Latto *et al.*,^{V48} although the temperature ranges of these studies overlap each other. Goring *et al.*^{V54} employed a capillary viscometer. Their measurement was carried out at comparatively large Reynolds numbers and measurement of the flow rate of air also seemed to be unreliable. For these reasons, these two sets of data were excluded. The data of Kurin *et al.*^{V55} were obtained in a Rankine viscometer and, generally speaking, the viscosity measured by this type of a viscometer is less reliable in the case of many other fluids. However, the density dependence of the data of Kurin^{V55} in the density range 400–880 kg/m³ was consulted with smaller assigned weight in the correlation of the viscosity, since no reliable data are available above 400 kg/m³.

Finally, the two sets of data of Kestin *et al.* in 1959,^{V42,V43} as well as the data of Kestin *et al.* (1964),^{V45} of Latto *et al.* (1973),^{V48} of Kurin *et al.* (1974),^{V55} and of Timrot *et al.* (1975),^{V49} were selected as reference data for the dense gaseous region. The isotherm at 523 K of Kestin *et al.* (1964)^{V45} was, however, excluded since this isotherm showed considerably different density dependence from other isotherms of the same report.

For the viscosity of air in the liquid region, there exist

Table 6. Selected sources on the viscosity of air at high pressure

First author	Year	Method	Temperature (K)	Pressure (MPa)	Ref.
Kestin	1959a	Oscill.disk	293 - 298	0.1 - 7	V42
Kestin	1959b	Oscill.disk	293	0.1 - 10	V43
Kestin	1964	Oscill.disk	298 - 523	0.1 - 14	V45
Latto	1973	Capillary	100 - 400	0.1 - 15	V48
Kurin*	1974	Capillary	293 - 323	9.8 - 324	V55
Timrot	1975	Oscill.disk	295 - 570	0.1 - 12	V49

* See text.

three reports for the saturated liquid, namely, Verschaffelt and Nicaise (1917),^{V56} Rudenko (1939),^{V57} and Naiki, Hanai, and Shimizu (1953),^{V58} and two sets of data of Filippova and Ishkin (1959,1961)^{V41,V53} for compressed liquid. The results of the three studies along the saturation line^{V56-V58} differ by scores of percent from each other. The data of Filippova *et al.*^{V41,V53} were, as mentioned above, not judged to be reliable. Therefore, no data for the liquid region were selected.

The selected data for the viscosity of air at high pressure are listed in Table 6.

3.3. Correlation and Tables

In the present study, the viscosity of air in the gaseous phase was correlated with the aid of an equation of the following form:

$$\eta(T, \rho) = \eta_0(T) + \Delta\eta(\rho), \quad (2)$$

where $\eta_0(T)$ represents the viscosity at sufficiently low pressure and $\Delta\eta(\rho)$ represents the excess viscosity. Since the pressure dependence of the viscosity of air is very small at sufficiently low pressures, $\eta_0(T)$ can be expressed as a function of temperature alone. The Chapman–Enskog theory suggests that the equation for $\eta_0(T)$ be expressed in the following form:

$$\eta_0(T) = (A \cdot T^{0.5}) / \Omega. \quad (2a)$$

Some studies used Eq. (2a) in correlating experimental viscosity data. The collision integral Ω was often expressed as an inverse-power series in temperature. However, in this study, Eq. (2a) was not adopted, in order for $\eta_0(T)$ and $\lambda_0(T)$,

Table 7. Constants in Eq. (3)

T*	132.5 (K)	B ₁	0.4656 01
ρ*	314.3 (kg/m ³)	B ₂	1.2646 9
H	6.1609 0 (10 ⁻⁶ Pa.s)	B ₃	-0.5114 25
		B ₄	0.2746 00
A ₁	0.1285 17		
A _{0.5}	2.6066 1		
A ₀	-1.0000 0		
A ₋₁	-0.7096 61		
A ₋₂	0.6625 34		
A ₋₃	-0.1978 46		
A ₋₄	0.0077 0147		

Table 8. Viscosity of air calculated with Eq. (3) (10^{-6} Pa·s)

T(K) \ P(MPA)	85.0	90.0	100.0	120.0	140.0	160.0	180.0	200.0
0.01	5.979	6.359	7.075	8.420	9.708	10.95	12.16	13.32
0.10	6.016	6.394	7.105	8.445	9.729	10.97	12.17	13.33
0.50			7.281	8.577	9.837	11.06	12.25	13.40
1.00				8.808	10.01	11.20	12.37	13.50
2.50					10.89	11.81	12.84	13.89
5.00						13.87	14.16	14.89
7.50						18.47	16.34	16.34
10.00						24.93	19.44	18.25
12.50							23.06	20.53
15.00							26.68	23.02
17.50							30.04	25.56
20.00								28.05
22.50								30.46
25.00								32.76
27.50								34.96
30.00								37.06

T(K) \ P(MPA)	250.0	300.0	350.0	400.0	450.0	500.0	550.0	600.0	650.0
0.01	16.04	18.56	20.90	23.09	25.16	27.13	29.01	30.82	32.56
0.10	16.06	18.57	20.90	23.10	25.17	27.13	29.02	30.82	32.57
0.50	16.11	18.61	20.94	23.13	25.20	27.16	29.04	30.85	32.59
1.00	16.19	18.67	20.99	23.17	25.23	27.20	29.07	30.87	32.61
2.50	16.46	18.89	21.17	23.32	25.36	27.31	29.17	30.97	32.69
5.00	17.09	19.35	21.53	23.62	25.62	27.53	29.37	31.14	32.85
7.50	17.90	19.91	21.97	23.97	25.91	27.78	29.59	31.34	33.03
10.00	18.88	20.57	22.46	24.37	26.24	28.07	29.84	31.56	33.23
12.50	20.00	21.32	23.02	24.81	26.61	28.38	30.11	31.80	33.44
15.00	21.23	22.12	23.62	25.29	27.00	28.71	30.40	32.05	33.67
17.50	22.55	22.98	24.25	25.79	27.42	29.06	30.70	32.32	33.91
20.00	23.93	23.89	24.92	26.32	27.85	29.43	31.02	32.60	34.15
22.50	25.34	24.82	25.61	26.86	28.30	29.81	31.35	32.89	34.41
25.00	26.77	25.78	26.32	27.43	28.76	30.21	31.69	33.19	34.68
27.50	28.21	26.76	27.05	28.00	29.24	30.61	32.04	33.50	34.96
30.00	29.64	27.75	27.79	28.59	29.72	31.02	32.40	33.81	35.24
35.00	32.47	29.76	29.31	29.79	30.72	31.87	33.13	34.46	35.82
40.00	35.23	31.78	30.84	31.02	31.74	32.74	33.89	35.13	36.42
45.00	37.93	33.79	32.40	32.27	32.78	33.63	34.66	35.81	37.03
50.00	40.55	35.79	33.96	33.53	33.83	34.53	35.45	36.51	37.65
55.00	43.10	37.78	35.53	34.81	34.90	35.44	36.25	37.22	38.29
60.00	45.59	39.74	37.10	36.09	35.98	36.37	37.06	37.94	38.94
65.00	48.01	41.69	38.67	37.39	37.07	37.31	37.88	38.67	39.59
70.00	50.38	43.62	40.23	38.69	38.17	38.26	38.72	39.41	40.26
75.00	52.69	45.52	41.80	39.99	39.28	39.22	39.56	40.16	40.93
80.00		47.41	43.36	41.30	40.40	40.19	40.41	40.92	41.62
85.00		49.28	44.91	42.61	41.53	41.17	41.28	41.69	42.31
90.00		51.13	46.46	43.93	42.66	42.17	42.16	42.48	43.01
95.00		52.97	48.01	45.25	43.81	43.17	43.05	43.27	43.73
100.00		54.79	49.55	46.58	44.96	44.19	43.95	44.08	44.46

Table 8. Viscosity of air calculated with Eq. (3) (10^{-6} Pa·s) (continued)

P(MPA)	T(K)	700.0	750.0	800.0	850.0	900.0	950.0	1000.0	1100.0	1200.0
0.01		34.24	35.88	37.46	39.01	40.51	41.98	43.42	46.21	48.90
0.10		34.25	35.88	37.47	39.01	40.52	41.99	43.43	46.22	48.91
0.50		34.27	35.90	37.48	39.02	40.53	42.00	43.44	46.23	48.92
1.00		34.29	35.92	37.50	39.04	40.55	42.02	43.45	46.24	48.93
2.50		34.37	35.99	37.57	39.11	40.61	42.07	43.51	46.29	48.97
5.00		34.51	36.12	37.69	39.22	40.71	42.17	43.60	46.37	49.05
7.50		34.67	36.27	37.83	39.35	40.83	42.28	43.70	46.47	49.13
10.00		34.85	36.43	37.98	39.48	40.96	42.40	43.82	46.57	49.22
12.50		35.04	36.61	38.14	39.63	41.10	42.53	43.94	46.67	49.32
15.00		35.25	36.79	38.31	39.79	41.24	42.66	44.06	46.78	49.42
17.50		35.46	36.99	38.49	39.95	41.39	42.81	44.19	46.90	49.52
20.00		35.69	37.19	38.67	40.12	41.55	42.95	44.33	47.02	49.63
22.50		35.92	37.41	38.87	40.30	41.72	43.11	44.47	47.15	49.74
25.00		36.16	37.62	39.07	40.49	41.89	43.26	44.62	47.28	49.86
27.50		36.41	37.85	39.27	40.68	42.06	43.43	44.77	47.41	49.97
30.00		36.66	38.08	39.48	40.87	42.24	43.59	44.93	47.55	50.10
35.00		37.19	38.56	39.92	41.27	42.61	43.94	45.25	47.83	50.35
40.00		37.73	39.05	40.37	41.69	43.00	44.30	45.59	48.13	50.61
45.00		38.28	39.55	40.83	42.12	43.40	44.67	45.93	48.43	50.89
50.00		38.85	40.07	41.31	42.55	43.80	45.05	46.29	48.75	51.17
55.00		39.42	40.60	41.79	43.00	44.22	45.43	46.65	49.07	51.45
60.00		40.01	41.13	42.28	43.46	44.64	45.83	47.02	49.39	51.75
65.00		40.60	41.67	42.78	43.92	45.07	46.23	47.40	49.73	52.04
70.00		41.21	42.22	43.29	44.39	45.51	46.64	47.78	50.06	52.35
75.00		41.82	42.78	43.80	44.86	45.95	47.05	48.16	50.41	52.66
80.00		42.44	43.35	44.33	45.35	46.40	47.47	48.56	50.76	52.97
85.00		43.07	43.93	44.86	45.84	46.85	47.89	48.96	51.11	53.28
90.00		43.71	44.51	45.39	46.33	47.31	48.33	49.36	51.47	53.61
95.00		44.36	45.11	45.94	46.84	47.78	48.76	49.77	51.83	53.93
100.00		45.02	45.71	46.50	47.35	48.26	49.21	50.18	52.20	54.26

P(MPA)	T(K)	1300.0	1400.0	1500.0	1600.0	1700.0	1800.0	1900.0	2000.0
0.01		51.51	54.03	56.48	58.87	61.20	63.49	65.72	67.91
0.10		51.51	54.03	56.48	58.87	61.21	63.49	65.72	67.91
0.50		51.52	54.04	56.49	58.88	61.21	63.49	65.73	67.92
1.00		51.53	54.05	56.50	58.89	61.22	63.50	65.74	67.93
2.50		51.57	54.09	56.54	58.92	61.25	63.53	65.76	67.95
5.00		51.64	54.15	56.60	58.98	61.30	63.58	65.81	67.99
7.50		51.71	54.22	56.66	59.04	61.36	63.63	65.86	68.04
10.00		51.79	54.29	56.73	59.10	61.42	63.69	65.91	68.09
12.50		51.88	54.37	56.80	59.16	61.48	63.74	65.96	68.14
15.00		51.97	54.45	56.87	59.23	61.54	63.80	66.02	68.19
17.50		52.06	54.54	56.95	59.30	61.61	63.86	66.07	68.24
20.00		52.16	54.62	57.03	59.38	61.68	63.93	66.13	68.30
22.50		52.26	54.71	57.11	59.45	61.75	63.99	66.20	68.36
25.00		52.36	54.81	57.20	59.53	61.82	64.06	66.26	68.42
27.50		52.47	54.90	57.29	59.61	61.89	64.13	66.32	68.48
30.00		52.58	55.00	57.38	59.70	61.97	64.20	66.39	68.54
35.00		52.80	55.21	57.56	59.87	62.13	64.35	66.53	68.67
40.00		53.04	55.42	57.76	60.05	62.29	64.50	66.67	68.80
45.00		53.28	55.64	57.96	60.23	62.47	64.66	66.82	68.94
50.00		53.53	55.87	58.17	60.42	62.64	64.82	66.97	69.08
55.00		53.79	56.10	58.38	60.62	62.82	64.99	67.13	69.23
60.00		54.05	56.34	58.60	60.82	63.01	65.16	67.29	69.38
65.00		54.32	56.58	58.82	61.02	63.20	65.34	67.45	69.53
70.00		54.59	56.83	59.05	61.23	63.39	65.52	67.62	69.69
75.00		54.87	57.08	59.28	61.45	63.59	65.70	67.79	69.85
80.00		55.15	57.34	59.51	61.66	63.79	65.89	67.96	70.01
85.00		55.43	57.60	59.75	61.88	63.99	66.08	68.14	70.18
90.00		55.72	57.86	59.99	62.10	64.19	66.27	68.32	70.34
95.00		56.02	58.13	60.23	62.32	64.40	66.46	68.50	70.51
100.00		56.31	58.40	60.48	62.55	64.61	66.65	68.68	70.69

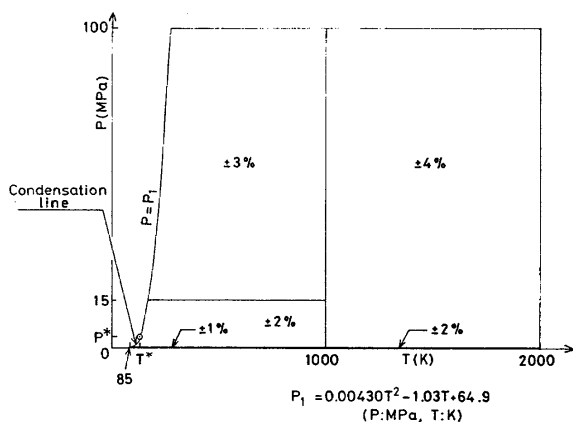


FIG. 2. Region of validity and the estimated uncertainty of Eq. (3).

the thermal conductivity at sufficiently low pressures, to be represented by an identical functional form. The functional form of $\lambda_0(T)$ will be explained later in Sec. 4.3. The following form is adopted for the equation for $\eta_0(T)$ of air:

$$\eta_0(T) = k_1 T + k_{0.5} T^{0.5} + \sum_{i=0}^{-4} k_i T^i \quad (2b)$$

Equation (2b) has proved itself to be suitable also for the correlation of the viscosity of air over a wide range of temperature.

The excess viscosity $\Delta\eta(\rho)$ was correlated with the aid of a power series in density. As mentioned in Sec. 3.2, temperature dependence of the excess viscosity $\Delta\eta$ of air is not obviously observed. Furthermore, it is necessary for extrapolating the resulting equation safely to as high as 2000 K to correlate $\Delta\eta$ as a function of density alone.

Since the experimental verification of the critical enhancement of the viscosity of air is not available as yet, Eq.

(2) does not contain a term for the critical enhancement. In the case of the viscosity, the critical enhancement is much less significant than that for the thermal conductivity and appears only in a narrow range of the critical region. Therefore, for all intents and purposes, Eq. (2) is sufficient in all regions of the gaseous phase.

The following equation was used for the correlation of the viscosity of the reference data selected in Sec. 3.2:

$$\eta(T_r, \rho_r) = H \cdot [\eta_0(T_r) + \Delta\eta(\rho_r)] \quad (3)$$

where

$$\eta_0(T_r) = A_1 T_r + A_{0.5} T_r^{0.5} + \sum_{i=0}^{-4} A_i T_r^i \quad (3a)$$

$$\Delta\eta(\rho_r) = \sum_{i=1}^4 B_i \rho_r^i \quad (3b)$$

$$T_r = T/T^* \quad (3c)$$

and

$$\rho_r = \rho/\rho^* \quad (3d)$$

The constants for Eq. (3) are listed in Table 7. The calculated viscosity of air using Eq. (3) is given in Table 8.

The region of validity and the estimated uncertainty of Eq. (3) is shown in Fig. 2. As explained earlier, the liquid region is not covered by the present correlation. Above 1000 K, the uncertainty for $\eta_0(T)$ is increased to $\pm 2\%$, because of the scarcity of experimental data. In the region up to 15 MPa, and up to 1000 K, the uncertainty of the correlation is assumed to be $\pm 2\%$, considering the reliability of available data.

3.4. Discussion

As shown in Fig. 3, the agreement of the reference data at low pressures with Eq. (3) is very good. Although the data of Matthews *et al.*⁵⁰ seem to be slightly lower than Eq. (3) at

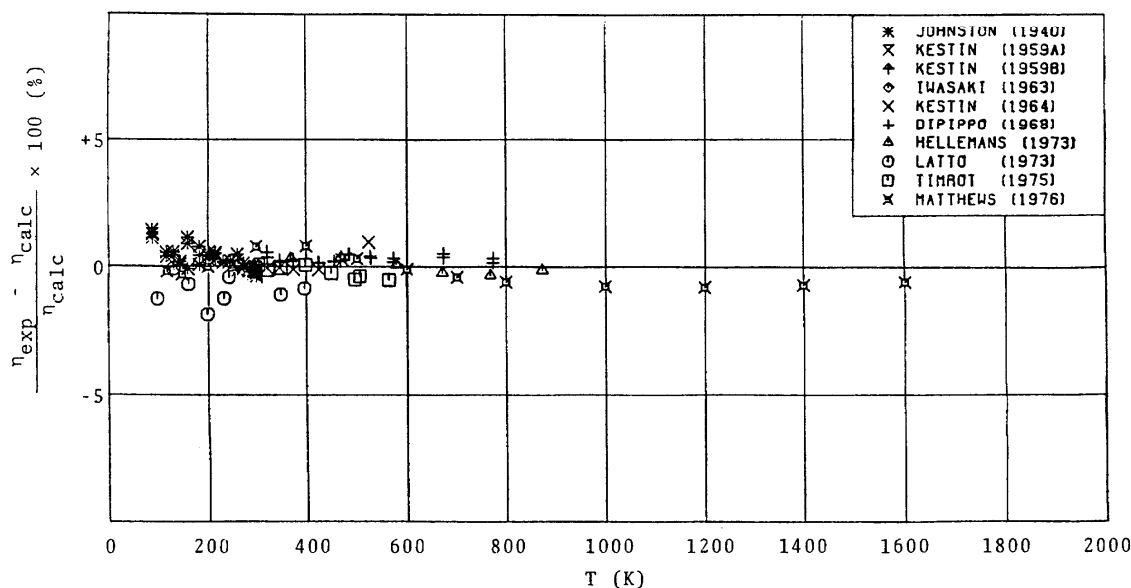


FIG. 3. Deviations of selected data from Eq. (3) (viscosity, 1 atm).

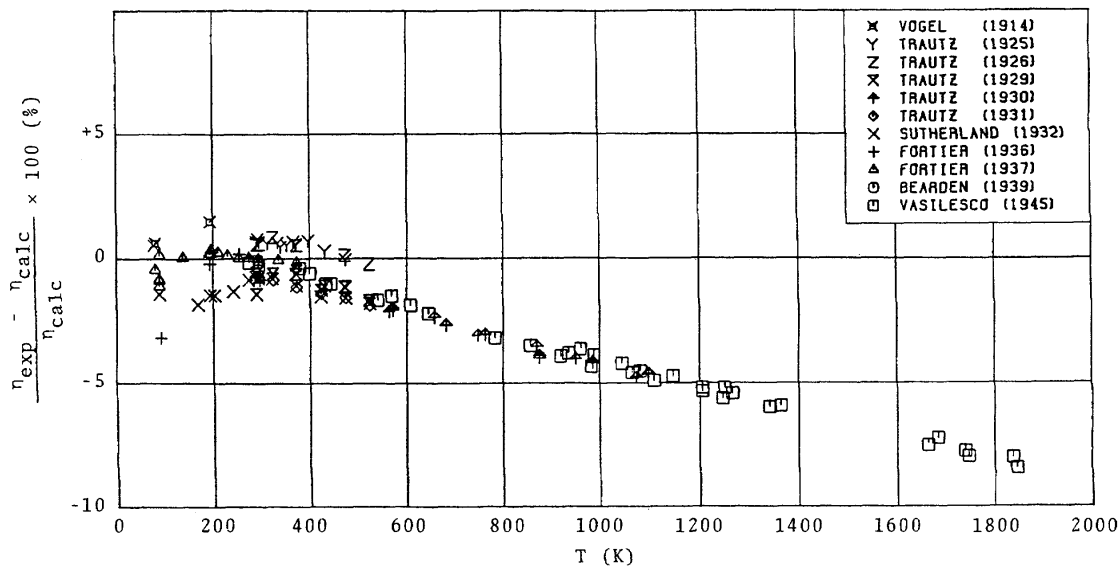


FIG. 4. Deviations of other data from Eq. (3) (viscosity, 1 atm).

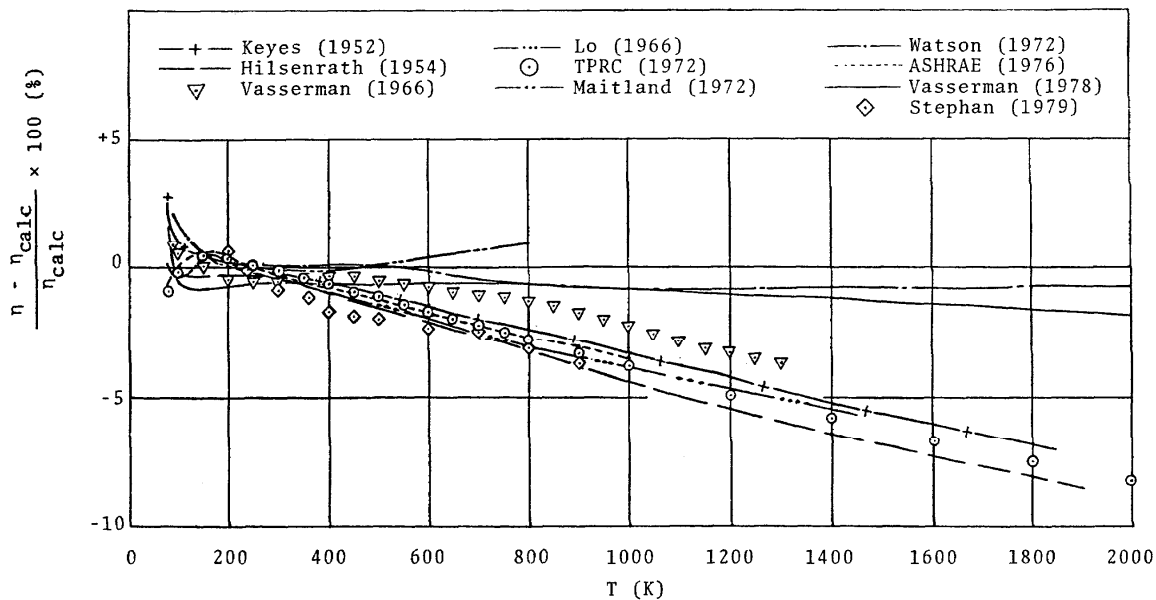


FIG. 5. Deviations of previous correlations from Eq. (3) (viscosity, 1 atm).

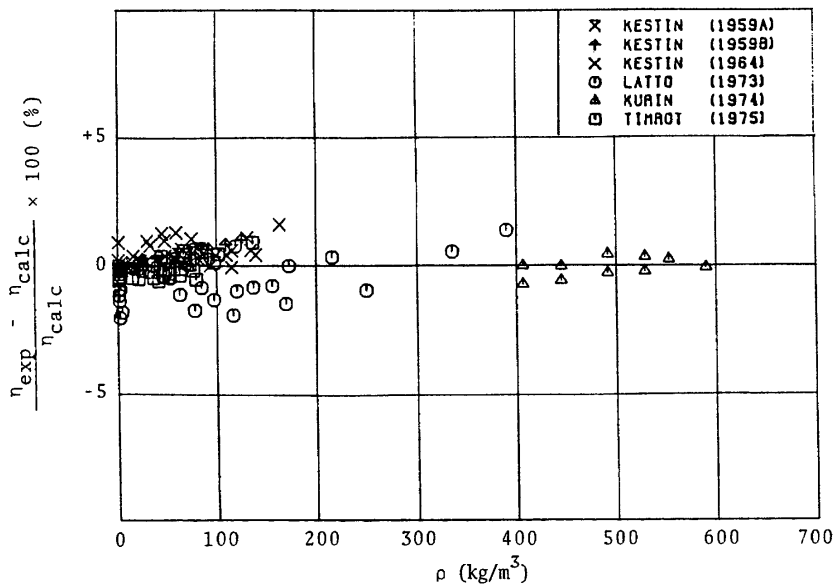


FIG. 6. Deviations of selected data from Eq. (3) (viscosity, high pressure).

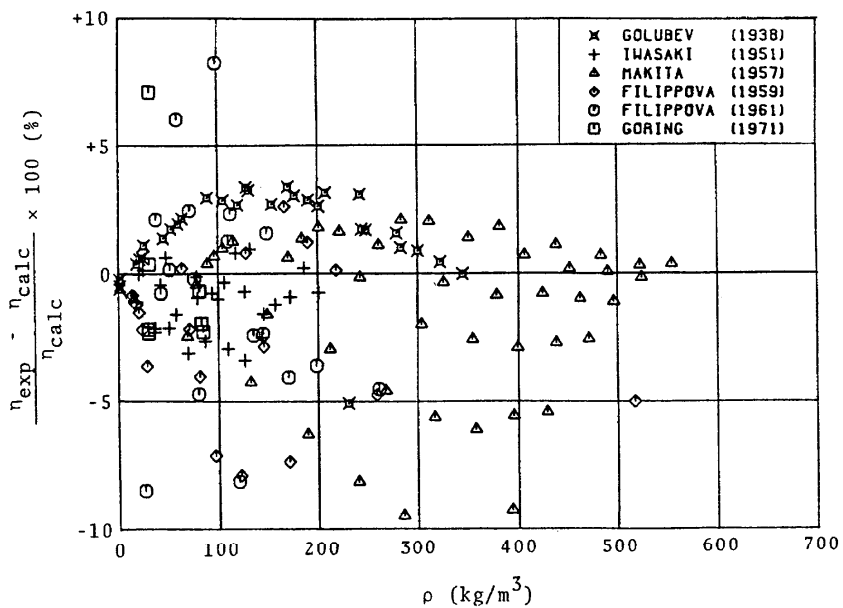


FIG. 7. Deviations of other data from Eq. (3) (viscosity, high pressure).

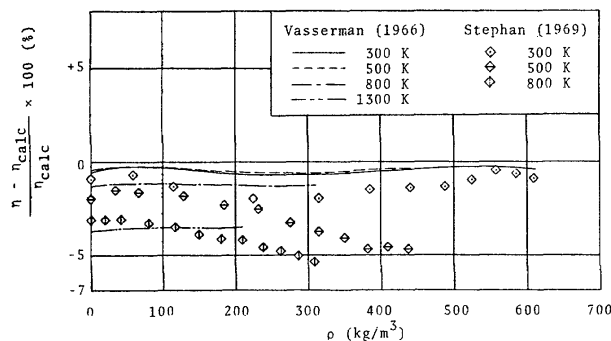


FIG. 8. Deviations of previous correlations from Eq. (3) (viscosity, high pressure).

higher temperatures, the plots are for the smoothed data given in Ref. V50, and Eq. (3) was fitted to the raw data (read from the deviation plots of Ref. V50). The agreement at room temperature is excellent. A comparison of some other data with Eq. (3) is shown in Fig. 4. These older data show significant deviations from the recent data.

As shown in Fig. 5, most of the existing recommendations and formulations of the viscosity of air found in literature give systematically lower values than Eq. (3) at higher temperatures, since these correlations are based on the data shown in Fig. 4. The recent two formulations at atmospheric pressure of Watson (1972)^{R8} and of Vasserman, Tsymarnyi, Skamorina, and Svetlichnaya (1978)^{R10} agree well with Eq. (3).

The comparison of the reference data at high pressures with Eq. (3) is shown in Fig. 6 as a function of density. Only for the data of Kurin *et al.*^{V55} above 100 MPa, was the density calculated using the equation of Baehr *et al.*¹ The reference data agree with Eq. (3) within $\pm 2\%$. Some other data are compared with Eq. (3) in Fig. 7.

In Fig. 8, Eq. (3) is compared with the formulation of Vasserman *et al.* (1966)² and the recommendation of Stephan *et al.* (1979)^{R11} for the viscosity of air at high pressures. The agreement is fair at 300 K, but the discrepancy becomes larger with increasing temperature. The reason for this discrepancy is the different selection of the reference data for η_0 as seen in Figs. 3, 4, and 5.

4. Thermal Conductivity

4.1. General Remarks

Generally speaking, the experimental uncertainty of the thermal conductivity is larger than that of the viscosity, since the measurement of the thermal conductivity is more difficult due to the effect of natural convection. Considerable scatter is observed in most of the data at high pressures.

In early studies, the steady-state hot wire method was most widely used, but, in recent years, the transient hot wire method has been used more and more often. The experimental data of the thermal conductivity of air at low pressures are available in the temperature range from 90 to 1200 K (Refs. T1–T33). Only a limited number of experimental data is available at high pressures (Refs. T8, T14, T25, T26, T30,

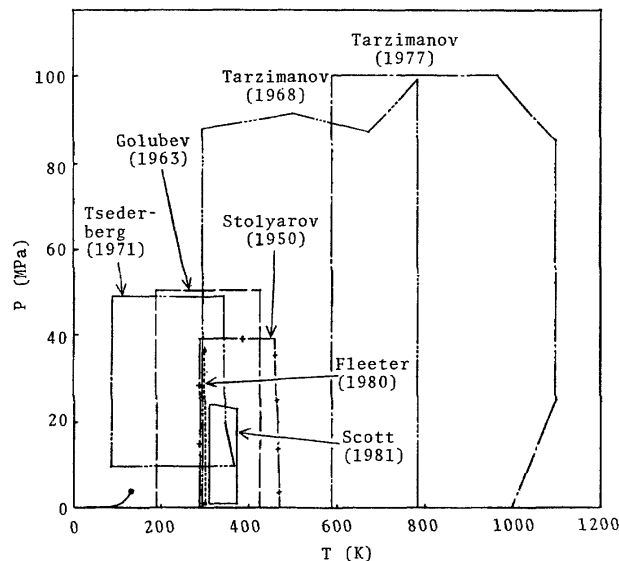


FIG. 9. Regions of experimental data on the thermal conductivity of air at high pressure.

T32, T33). The measurements in the liquid region were performed only by Tsederberg and Ivanova (1971).^{T26} The regions of available data of the thermal conductivity of air at high pressures are shown in Fig. 9. The region covered is wider than that for the viscosity.

A number of reviews on the thermal conductivity of air are available (Refs. 2, R2, R9, R10, R12–R15). Among them, the reviews by Hilsenrath and Touloukian (1954),^{R2} by Vasserman *et al.* (1966),² by TPRC (1970),^{R14} and by Vargaftik, Filippov, Tarzimanov, and Totkii (1978)^{R15} cover a wide range of temperature. However, equations in most of these reviews are based on rather old data.

Among the experimental data at low pressures, the data published before 1960 were, as in the case of the viscosity, screened on the basis of the existing reviews (Refs. R14, R15). All the data after 1960 were analyzed in the evaluating process.

In the case of the experimental thermal conductivity data at high pressures, all the data were taken into consideration. Since enough number of reliable data were not available, the liquid region was not included in the range of validity of the present correlation.

4.2. Selection of Data

As for low pressures, although the experimental data are available at temperatures from 90 to 1200 K, most of them concentrate around room temperature. Among the 23 sets of data published since 1960, 18 sets are available around room temperature (270–370 K).^{T12–T14, T17–T27, T30–T33} After detailed examination of these reports, three sets of data obtained by the transient hot wire method, namely, the data of Briggs, Goldstein, and Ibele (1968),^{T24} of Fleeter, Kestin, and Wakeham (1980),^{T32} and of Scott, Johns, Watson, and Clifford (1981)^{T33} were judged to be the most reliable. Slightly smaller weight was given to the data of Briggs *et al.*^{T24}

than that to the recent two sets of data,^{T32,T33} which agree well with each other. In addition, the data of Golubev (1963)^{T14} by the bicalorimeter method (a transient method with a concentric-cylinder apparatus) and the data of Rastorguev and Geller (1967)^{T22} and of Irving, Jamieson and Paget (1973),^{T29} both obtained by the steady-state hot wire method, were also consulted with small weight.

In the high-temperature region (above 370 K), seven sets of data, namely, the data of Vines (1960),^{T11} of Geier and Schäfer (1961),^{T12} of Baker and Brokaw (1964),^{T16} of Tarzimanov and Lozovoi (1968),^{T25} of Mustafaev (1972),^{T28} of Tarzimanov and Salmanov (1977),^{T30} and of Guseinov and Klimova (1980),^{T31} are available. The data of Geier, Schäfer and co-workers for other gases often show lower trend than the recent data at high temperatures and this is the case also for air. Detailed information on the sample air was insufficient in the report by Baker *et al.* (1964).^{T16} Their measurement was carried out on a relative basis and reference thermal conductivity data for He and Ar employed by them are not accurate. The two sets of data of Tarzimanov *et al.* in 1968 and in 1977^{T25,T30} do not agree well with each other. The more recent data of 1977^{T30} were taken into consideration. The dynamic method employed by Mustafaev (1972)^{T28} is not considered reliable and the measurement of air was carried out merely as a test run in his study. The measurement of Guseinov *et al.* (1980)^{T31} was also carried out as a test of their instrument and their published data seem to contain printing errors (or, their data are in serious error).

Finally, the data of Vines^{T11} and of the second set of data of Tarzimanov *et al.*^{T30} were selected in the high-temperature region. Smaller weight was assigned to the older data of Vines.^{T11}

In the low-temperature region (90–270 K), only the data of Tsederberg and Ivanova (1971)^{T26} were reported after 1960. However, they published no numerical data but an equation representing the experimental results. Without further information, an evaluation of their data could not be done satisfactorily. Consequently, in the low-temperature region, the present authors included the data published before 1960 in the analysis and finally selected the data of Taylor and Johnston (1946)^{T6} and of Kannuluik and Carman (1951).^{T9} Although the data of Taylor *et al.*^{T6} are older, the experiments seem to be more reliable. When their measurements were undertaken, the international practical temperature scale was not available at low temperatures and the thermocouples were calibrated using a hydrogen thermometer. Their correction for radiation heat loss seems too large and this might explain the reason why their data are slightly too low at room temperature. Therefore, their data above 300 K were left unused. The data of Kannuluik *et al.*^{T9} were also consulted with smaller assigned weight.

The selected data of the thermal conductivity at low pressures are summarized in Table 9.

At temperatures above 1200 K, no experimental data on the thermal conductivity of air are available. As in the case of the viscosity, assuming that air is a mixture of N₂, O₂, Ar, and CO₂, the thermal conductivity of dilute air was estimated from those of the component gases with the aid of the

Table 9. Selected sources on the thermal conductivity of air at atmospheric pressure

First author	Year	Method	Temperature (K)	Ref.
Taylor	1946	Hot-wire (s) ^a	87 - 375	T6
Kannuluik*	1951	Hot-wire (s)	90 - 490	T9
Vines*	1960	Conc.cyl.	510 - 1170	T11
Golubev*	1963	Conc.cyl.	200 - 430	T14
Rastorguev*	1967	Hot-wire (s)	300	T22
Briggs*	1968	Hot-wire (t) ^b	310 - 370	T24
Irving*	1973	Hot-wire (s)	273 - 450	T29
Tarzimanov	1977	Hot-wire (s)	400 - 1200	T30
Fleeter	1980	Hot-wire (t)	300	T32
Scott	1981	Hot-wire (t)	312 - 373	T33

* See text.

a: Steady-state.

b: Transient.

mixing rules for the thermal conductivity reported in Refs. 10 and 13–18. The thermal conductivity values and the intermolecular potential parameters of the component gases employed in the estimation were taken from a report by the present authors.⁵ The thermal conductivity values estimated by different methods agree well with each other over the entire temperature range, except the result with the method proposed in Ref. 17. Although a small systematic discrepancy is observed, estimated thermal conductivity values are in accord with the temperature dependence of the experimental data of Tarzimanov *et al.* (1977)^{T30} above 600 K. Therefore, Tarzimanov's data of up to 1200 K were extrapolated to 2000 K, using the temperature dependence of the estimated values.

It is known that the excess thermal conductivity of a pure gas can be expressed as a function of density alone at regions where critical enhancement is insignificant. As will be mentioned later, available experimental data for dense gaseous air suggest that the excess thermal conductivity of air can also be assumed to be a function of density alone. With this assumption, the data at different temperatures can, as in the case of the viscosity, be compared with each other.

The pressure dependence of the thermal conductivity of air was first measured by Stolyarov, Ipatev, and Teodorovich (1950).^{T8} Their data are systematically lower than the recent data, for example, at most 8.5% lower than the data of Scott *et al.*^{T33} A similar tendency is observed for their data on nitrogen. The existence of a maximum, which seems to suggest the critical enhancement, is observed on the isotherm at 196 K of thermal conductivity data of Golubev (1963).^{T14} But, the temperature where the maximum is observed is much larger than that expected from the analogy with some pure gases. The data of Tarzimanov *et al.* (1968)^{T25} show a stronger temperature dependence than that observed in their data in 1977.^{T30} The data of Tsederberg *et al.* (1971),^{T26} obtained at densities up to 950 kg/m³, show considerable scatter. For these reasons, all the data published before 1971 were omitted. But the data by Tsederberg *et al.*^{T26} in the density range 400–950 kg/m³ were taken into

Table 10. Selected sources on the thermal conductivity of air at high pressure

First author	Year	Method	Temperature (K)	Pressure (MPa)	Ref.
Tsederberg*	1971	Hot-wire (s) ^a	80 - 340	0.1 - 50	T26
Tarzmanov	1977	Hot-wire (s)	400 - 1200	0.1 - 100	T30
Fleeter	1980	Hot-wire (t) ^b	300	0.8 - 36	T32
Scott	1981	Hot-wire (t)	312 - 373	0.9 - 23	T33

* See text.

a: Steady-state.

b: Transient.

consideration with smaller weight, since no other data were available at these densities. It should be noted here that only the data of Tsederberg *et al.*^{T26} cover the liquid region.

Finally, the data of Tsederberg *et al.* (1971),^{T26} of Tarzmanov *et al.* (1977),^{T30} of Fleeter *et al.* (1980),^{T32} and of Scott *et al.* (1981)^{T33} were selected. Although Fleeter's data have been most highly trusted, it must be remembered that they were taken only at a single temperature. The excess thermal conductivity derived from Tarzmanov's data of 1977,^{T30} obtained in the temperature range 590–1100 K, show almost no temperature dependence, except for the isotherm at 900 K, which shows a slightly higher trend. Since the data of Tarzmanov *et al.*^{T30} are systematically higher by 2% or 3% than those of Fleeter *et al.*^{T32} and of Scott *et al.*,^{T33} larger weight was given to the latter two sets.

The selected data of the thermal conductivity at high pressures are listed in Table 10.

4.3. Correlation and Tables

In the present study, the thermal conductivity of gaseous air was correlated into the equation,

$$\lambda(T, \rho) = \lambda_0(T) + \Delta\lambda(\rho), \quad (4)$$

where $\lambda_0(T)$ is the thermal conductivity at sufficiently low pressures and $\Delta\lambda(\rho)$ is the excess thermal conductivity. Since the pressure dependence of the thermal conductivity of air is very weak at sufficiently low pressures, $\lambda_0(T)$ can be treated as a function of temperature alone.

In the case of the thermal conductivity, the so-called critical enhancement is much more significant than that for the viscosity. But, in the critical region of air as mentioned in Sec. 4.2, no reliable experimental data of the thermal conductivity are available. Critical enhancement is, therefore, not considered in the present correlation and a limited range in the critical region has to be deleted from the range of validity as explained later. The excess thermal conductivity can be treated as a function of density alone, except for this excluded region. The reason why no temperature-dependent terms have been introduced in $\Delta\lambda$ is the same as that for the excess viscosity $\Delta\eta$ (see Sec. 3.3).

$\lambda_0(T)$ of monatomic gases can be well expressed by a functional form similar to Eq. (2a). However, in the case of polyatomic gases, the contribution of the internal degrees of freedom of the molecule, which is closely related to the heat capacity at constant volume $c_{v,0}(T)$, is significant. It is known

Table 11. Constants in Eq. (5)

T*	132.5 (K)	D ₁	0.4022 87
ρ^*	314.3 (kg/m ³)	D ₂	0.3566 03
Λ	25.9778 (10 ⁻³ W/(m.K))	D ₃	-0.1631 59
		D ₄	0.1380 59
		D ₅	-0.0201 725
C ₁	0.2395 03		
C _{0.5}	0.0064 9768		
C ₀	1.0000 0		
C ₋₁	-1.9261 5		
C ₋₂	2.0038 3		
C ₋₃	-1.0755 3		
C ₋₄	0.2294 14		

empirically that the function $c_{v,0}(T)$ can be successfully correlated by a power series in the temperature,

$$c_{v,0}(T) = \sum_{i=-m}^n l_i T^i \quad (m > 0, n > 0). \quad (4a)$$

The following formula, obtained by combining Eqs. (2a) and (4a), is an option for the functional form of $\lambda_0(T)$:

$$\lambda_0(T) = \frac{A \cdot T^{0.5}}{\Omega} \cdot \sum_{i=-m}^n k_i T^i, \quad (4b)$$

where Ω can be expressed as an inverse-power series of T . However, a much simpler formula,

$$\lambda_0(T) = k_1 T + k_{0.5} T^{0.5} + \sum_{i=0}^{-4} k_i T^i, \quad (4c)$$

was found to be suitable to correlate $\lambda_0(T)$ of several gases as well as of air.

Based on the data selected in Sec. 4.2, the following equation for the thermal conductivity of air was adopted:

$$\lambda(T_r, \rho_r) = \Lambda [\lambda_0(T_r) + \Delta\lambda(\rho_r)], \quad (5)$$

where

$$\lambda_0(T_r) = C_1 T_r + C_{0.5} T_r^{0.5} + \sum_{i=0}^{-4} C_i T_r^i, \quad (5a)$$

$$\Delta\lambda(\rho_r) = \sum_{i=1}^5 D_i \rho_r^i, \quad (5b)$$

$$T_r = T/T^*, \quad (5c)$$

and

$$\rho_r = \rho/\rho^*. \quad (5d)$$

The constants for Eq. (5) are given in Table 11. The calculated thermal conductivity of air with the aid of Eq. (5) is given in Table 12.

The range of validity and the estimated uncertainty of Eq. (5) is shown in Fig. 10. It was presumed from the analogy with some pure gases,²¹ that Eq. (5) is not sufficiently accurate due to the critical enhancement in the following small range in the critical region:

$$T < 159 \text{ K}$$

and

$$P > 3.3 \text{ MPa.}$$

Table 12. Thermal conductivity of air calculated with Eq. (5) (10^{-3} W/(m·K))

T(K) \ P(MPA)	85.0	90.0	100.0	120.0	140.0	160.0	180.0	200.0
0.01	7.967	8.359	9.297	11.24	13.10	14.88	16.61	18.30
0.10	8.096	8.480	9.405	11.33	13.18	14.95	16.67	18.36
0.50			9.974	11.77	13.54	15.26	16.94	18.60
1.00				12.45	14.06	15.68	17.31	18.92
2.50					16.28	17.30	18.61	20.02
5.00						21.75	21.61	22.36
7.50						30.40	25.96	25.38
10.00						41.70	31.71	29.07
12.50							38.15	33.28
15.00							44.36	37.73
17.50							49.95	42.16
20.00								46.41
22.50								50.42
25.00								54.17
27.50								57.69
30.00								60.99

T(K) \ P(MPA)	250.0	300.0	350.0	400.0	450.0	500.0	550.0	600.0	650.0
0.01	22.37	26.20	29.81	33.25	36.53	39.69	42.75	45.71	48.61
0.10	22.41	26.23	29.84	33.28	36.56	39.71	42.77	45.73	48.63
0.50	22.60	26.39	29.98	33.39	36.66	39.81	42.85	45.81	48.70
1.00	22.85	26.59	30.15	33.54	36.79	39.92	42.96	45.91	48.79
2.50	23.66	27.24	30.69	34.01	37.20	40.29	43.29	46.21	49.07
5.00	25.22	28.44	31.67	34.84	37.93	40.93	43.86	46.73	49.55
7.50	27.03	29.77	32.74	35.73	38.69	41.61	44.47	47.28	50.04
10.00	29.06	31.21	33.87	36.67	39.49	42.31	45.09	47.84	50.56
12.50	31.26	32.74	35.05	37.64	40.32	43.03	45.73	48.42	51.08
15.00	33.61	34.34	36.28	38.65	41.18	43.77	46.39	49.01	51.62
17.50	36.05	36.00	37.55	39.68	42.05	44.53	47.06	49.61	52.17
20.00	38.55	37.70	38.85	40.73	42.94	45.30	47.75	50.23	52.72
22.50	41.08	39.43	40.17	41.80	43.84	46.09	48.44	50.84	53.28
25.00	43.60	41.19	41.50	42.88	44.75	46.88	49.13	51.47	53.85
27.50	46.09	42.95	42.85	43.98	45.67	47.67	49.84	52.10	54.42
30.00	48.54	44.72	44.21	45.08	46.60	48.47	50.54	52.73	55.00
35.00	53.29	48.25	46.94	47.29	48.47	50.09	51.97	54.01	56.15
40.00	57.83	51.72	49.67	49.52	50.35	51.72	53.41	55.30	57.32
45.00	62.13	55.13	52.39	51.75	52.24	53.35	54.85	56.59	58.50
50.00	66.23	58.46	55.08	53.98	54.13	55.00	56.31	57.90	59.68
55.00	70.13	61.70	57.75	56.21	56.03	56.65	57.76	59.20	60.86
60.00	73.85	64.86	60.38	58.42	57.92	58.30	59.23	60.52	62.05
65.00	77.40	67.92	62.97	60.62	59.82	59.96	60.70	61.84	63.25
70.00	80.81	70.91	65.52	62.80	61.71	61.62	62.18	63.17	64.46
75.00	84.08	73.82	68.03	64.97	63.60	63.28	63.66	64.50	65.67
80.00		76.65	70.49	67.12	65.49	64.95	65.15	65.84	66.89
85.00		79.42	72.92	69.25	67.37	66.63	66.65	67.20	68.12
90.00		82.12	75.31	71.37	69.25	68.30	68.16	68.56	69.36
95.00		84.75	77.66	73.46	71.12	69.98	69.67	69.93	70.61
100.00		87.33	79.98	75.54	72.98	71.67	71.19	71.32	71.88

Table 12. Thermal conductivity of air calculated with Eq. (5) (10^{-3} W/(m·K))
(continued)

T(K) P(MPA)	700.0	750.0	800.0	850.0	900.0	950.0	1000.0	1100.0	1200.0
0.01	51.45	54.23	56.98	59.68	62.36	65.00	67.62	72.80	77.91
0.10	51.46	54.25	56.99	59.69	62.37	65.01	67.63	72.81	77.92
0.50	51.53	54.31	57.05	59.75	62.42	65.06	67.68	72.85	77.96
1.00	51.61	54.39	57.12	59.82	62.48	65.12	67.74	72.90	78.00
2.50	51.87	54.63	57.35	60.03	62.68	65.31	67.91	73.06	78.15
5.00	52.31	55.04	57.73	60.39	63.02	65.63	68.22	73.34	78.40
7.50	52.77	55.46	58.12	60.76	63.37	65.96	68.53	73.62	78.66
10.00	53.24	55.90	58.53	61.14	63.72	66.29	68.84	73.90	78.92
12.50	53.72	56.34	58.94	61.52	64.09	66.63	69.17	74.19	79.18
15.00	54.22	56.80	59.36	61.92	64.45	66.98	69.49	74.49	79.45
17.50	54.72	57.26	59.79	62.32	64.83	67.33	69.83	74.79	79.72
20.00	55.23	57.73	60.23	62.72	65.21	67.69	70.16	75.09	80.00
22.50	55.74	58.20	60.67	63.13	65.59	68.05	70.50	75.40	80.27
25.00	56.26	58.68	61.11	63.54	65.98	68.41	70.85	75.70	80.55
27.50	56.78	59.16	61.56	63.96	66.37	68.78	71.19	76.02	80.83
30.00	57.30	59.64	62.00	64.38	66.76	69.15	71.54	76.33	81.12
35.00	58.36	60.62	62.91	65.22	67.55	69.89	72.24	76.96	81.69
40.00	59.43	61.61	63.82	66.08	68.35	70.64	72.95	77.60	82.27
45.00	60.51	62.60	64.74	66.93	69.15	71.40	73.67	78.24	82.85
50.00	61.59	63.59	65.67	67.79	69.96	72.16	74.38	78.88	83.44
55.00	62.67	64.59	66.60	68.66	70.77	72.92	75.10	79.53	84.03
60.00	63.76	65.60	67.53	69.53	71.59	73.69	75.83	80.19	84.62
65.00	64.86	66.61	68.47	70.41	72.41	74.46	76.56	80.84	85.22
70.00	65.96	67.63	69.41	71.29	73.23	75.24	77.29	81.50	85.82
75.00	67.07	68.65	70.36	72.17	74.06	76.02	78.02	82.16	86.42
80.00	68.19	69.68	71.31	73.06	74.89	76.80	78.76	82.82	87.02
85.00	69.32	70.72	72.28	73.96	75.73	77.59	79.51	83.49	87.62
90.00	70.45	71.76	73.25	74.86	76.58	78.38	80.26	84.16	88.23
95.00	71.60	72.82	74.23	75.77	77.43	79.18	81.01	84.84	88.85
100.00	72.76	73.89	75.22	76.69	78.29	79.99	81.77	85.52	89.46

T(K) P(MPA)	1300.0	1400.0	1500.0	1600.0	1700.0	1800.0	1900.0	2000.0
0.01	82.96	87.97	92.95	97.89	102.8	107.7	112.6	117.5
0.10	82.97	87.98	92.96	97.90	102.8	107.7	112.6	117.5
0.50	83.01	88.01	92.99	97.93	102.8	107.7	112.6	117.5
1.00	83.05	88.06	93.03	97.97	102.9	107.8	112.7	117.5
2.50	83.19	88.18	93.14	98.08	103.0	107.9	112.7	117.6
5.00	83.42	88.40	93.34	98.26	103.2	108.0	112.9	117.7
7.50	83.65	88.61	93.54	98.45	103.3	108.2	113.1	117.9
10.00	83.89	88.83	93.75	98.64	103.5	108.4	113.2	118.0
12.50	84.13	89.05	93.95	98.83	103.7	108.5	113.4	118.2
15.00	84.37	89.28	94.16	99.03	103.9	108.7	113.5	118.4
17.50	84.62	89.51	94.37	99.23	104.1	108.9	113.7	118.5
20.00	84.87	89.74	94.59	99.43	104.2	109.1	113.9	118.7
22.50	85.12	89.97	94.80	99.63	104.4	109.2	114.0	118.8
25.00	85.38	90.20	95.02	99.83	104.6	109.4	114.2	119.0
27.50	85.63	90.44	95.24	100.0	104.8	109.6	114.4	119.1
30.00	85.89	90.68	95.46	100.2	105.0	109.8	114.5	119.3
35.00	86.41	91.16	95.90	100.7	105.4	110.1	114.9	119.6
40.00	86.94	91.64	96.35	101.1	105.8	110.5	115.2	120.0
45.00	87.47	92.13	96.80	101.5	106.2	110.9	115.6	120.3
50.00	88.00	92.62	97.26	101.9	106.6	111.3	115.9	120.6
55.00	88.54	93.11	97.72	102.3	107.0	111.6	116.3	121.0
60.00	89.08	93.61	98.18	102.8	107.4	112.0	116.6	121.3
65.00	89.62	94.11	98.64	103.2	107.8	112.4	117.0	121.6
70.00	90.16	94.61	99.11	103.6	108.2	112.8	117.4	122.0
75.00	90.71	95.12	99.57	104.1	108.6	113.1	117.7	122.3
80.00	91.26	95.62	100.0	104.5	109.0	113.5	118.1	122.7
85.00	91.81	96.13	100.5	104.9	109.4	113.9	118.4	123.0
90.00	92.37	96.64	101.0	105.4	109.8	114.3	118.8	123.3
95.00	92.93	97.15	101.5	105.8	110.2	114.7	119.2	123.7
100.00	93.49	97.67	101.9	106.3	110.7	115.1	119.5	124.0

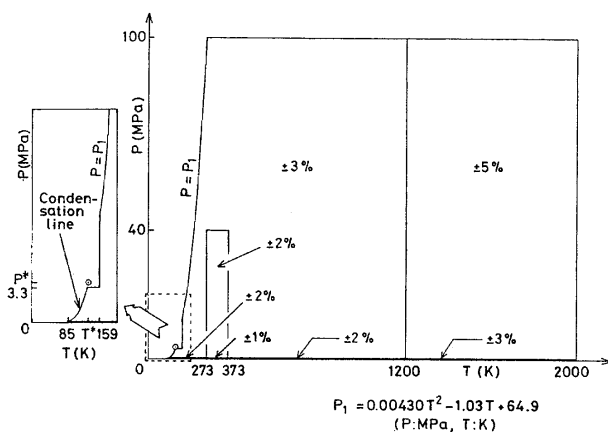


FIG. 10. Region of validity and the estimated uncertainty of Eq. (5).

4.4. Discussion

Deviation plots of experimental data at atmospheric pressure from Eq.(5) are shown in Figs. 11 and 12. In Fig. 11, we can see that agreement of the selected data with Eq. (5) is satisfactory. Around room temperature (270–370 K), the data of Fleeter *et al.* (1980)^{T32} and of Scott *et al.* (1981)^{T33} agree with Eq. (5) within $\pm 0.5\%$. The data of Rastorguev *et al.* (1967),^{T22} of Briggs *et al.*,^{T24} and of Irving *et al.* (1973)^{T29} agree within $\pm 2\%$. In the high-temperature region (above 370 K), the data of Tarzimanov *et al.* (1977)^{T30} and of Vines (1960)^{T11} agree with Eq. (5) within $\pm 1\%$. In the low-temperature region (up to 270 K), the data of Golubev (1963),^{T14} as well as of Taylor *et al.* (1946)^{T6} and of Kannuluik *et al.* (1951),^{T9} agree with Eq. (5) within $\pm 1.5\%$. As mentioned before, the data of Taylor *et al.*^{T6} are slightly lower than

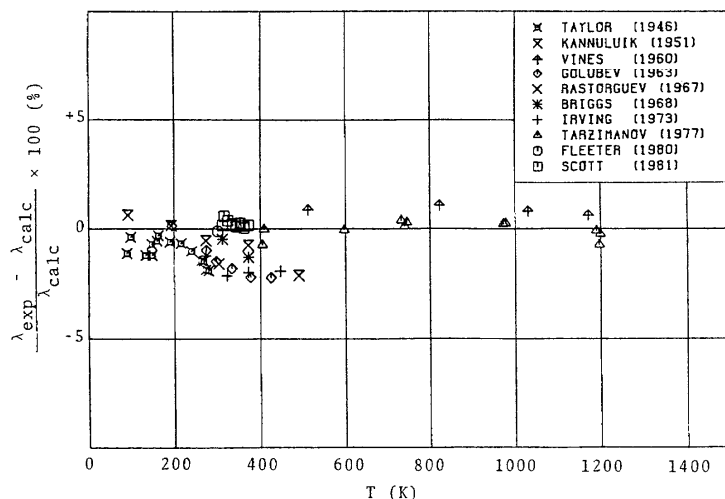


FIG. 11. Deviations of selected data from Eq. (5) (thermal conductivity, 1 atm).

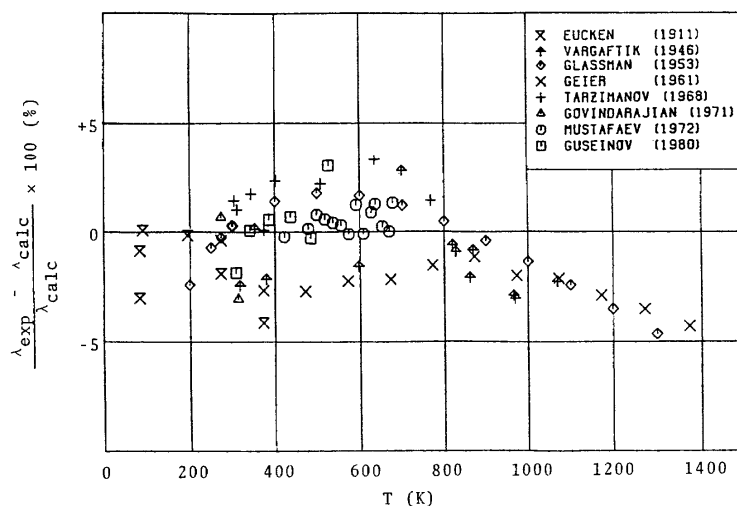


FIG. 12. Deviations of other data from Eq. (5) (thermal conductivity, 1 atm).

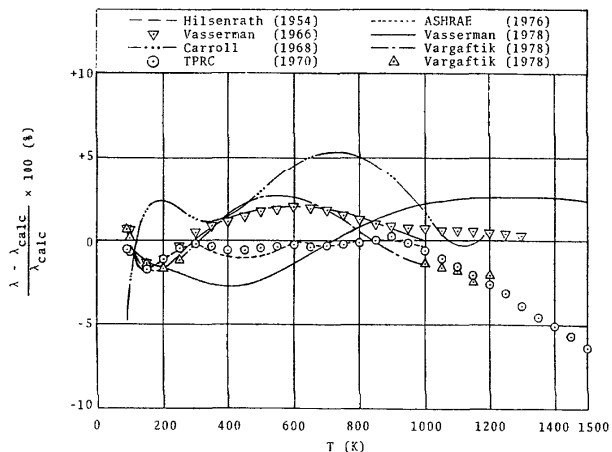


FIG. 13. Deviations of previous correlations from Eq. (5) (thermal conductivity, 1 atm).

those of Fleeter *et al.*^{T32} and of Scott *et al.*^{T33} at around room temperature, probably due to the incorrect correction for radiation heat loss in Taylor's study.

Figure 12 shows deviations of some other data at atmospheric pressure. The data of Glassman and Bonilla (1953)^{T10} and of Geier and Schäfer (1961)^{T12} show a systematically lower trend at high temperatures. If we take Zimina's explanation,²² the origin of this departure is that the correction for the temperature jump at the surface of the cylinder or the hot wire was inadequate in these older studies.

The systematic departure of older data from Eq. (5) is clearly seen at high temperatures also in Fig. 13, where recommended values of the thermal conductivity of air found in literature are compared with Eq. (5). At temperatures below 1000 K, these recommendations agree reasonably well with Eq. (5), except an equation by Carroll, Lo, and Stiel

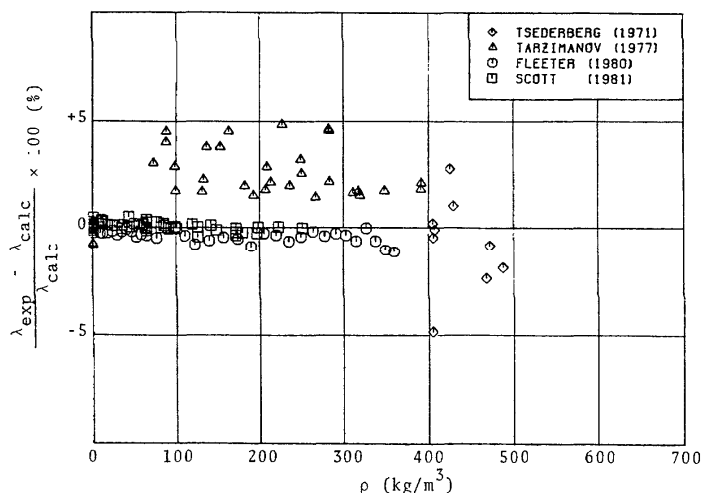


FIG. 14. Deviations of selected data from Eq. (5) (thermal conductivity, high pressure).

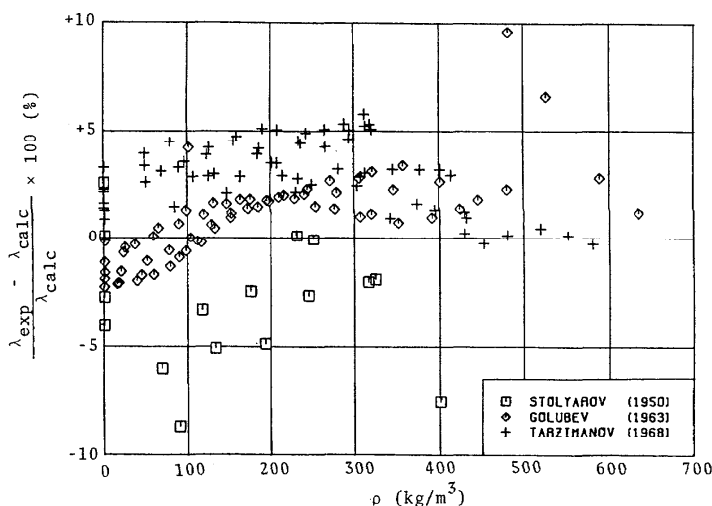


FIG. 15. Deviations of other data from Eq. (5) (thermal conductivity, high pressure).

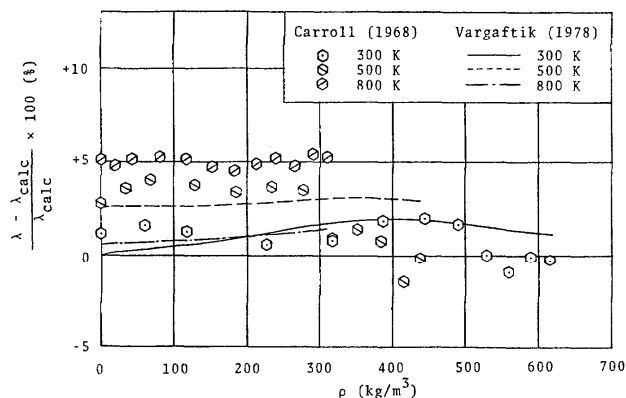


FIG. 16. Deviations of previous correlations from Eq. (5) (thermal conductivity, high pressure).

(1968).^{R13} At higher temperatures, the recommendations by TPRC (1970)^{R14} and by Vargaftik *et al.* (1978)^{R15} depart from Eq. (5) and the discrepancy increases with increasing temperature. The equation of Vasserman *et al.* (1978)^{R10} shows better but still unsatisfactory agreement at temperatures above 1000 K.

At high pressures, the deviations of the selected experimental data from Eq. (5) are depicted in Fig. 14 as a function of density. The data of Fleeter *et al.* (1980)^{T32} and of Scott *et al.* (1981)^{T33} agree with Eq. (5) within $\pm 1\%$. The deviations of the data of Tarzimanov *et al.* (1977)^{T30} are larger than those of the two recent sets of data. Equation (5) was correlated considering the density dependence of the data of Tse-derberg *et al.* (1971)^{T26} at densities above 400 kg/m³ including those in the liquid region. Deviations of some other data at high pressures are shown in Fig. 15.

In Fig. 16, the equations for the thermal conductivity of

air at high pressures of Carroll *et al.* (1968)^{R13} and of Vargaftik *et al.* (1978)^{R15} are compared with Eq. (5). The equation of Carroll *et al.*^{R13} gives a larger value at high temperatures, while, the equation of Vargaftik *et al.* (1978)^{R15} agrees fairly well with the present correlation.

5. Discussion on the Standard Values of the Viscosity and the Thermal Conductivity of Air

Since air is one of the most important gases, standard values of its properties are desirable.

Experimental viscosity values listed in Table 13 are those considered by many researchers to be the most accurate and are often used as calibration standards. Different experimental methods, namely the rotating cylinder,^{V30} the oscillating disk,^{V42-V47} and the capillary method,^{V50} were used to obtain the values listed in Table 13. Since Ref. V50 was not of the absolute measurement, any other capillary measurement would be valuable for additional confirmation. The present authors consider the measurement of nitrogen by Kurase, Kobayashi, and Kawata¹⁹ the most accurate determination of the gas viscosity among recent studies. They constructed an absolute capillary viscometer and determined the viscosity of nitrogen at 25 °C and 1 atm as 17.773×10^{-6} Pa·s. Older measurement of the viscosity of nitrogen by Kestin and Leidenfrost^{V42} shows a deviation of only 0.13%.

Equation (3a) of the present study agrees with experimental values in Table 13 within 0.2% at 20 °C and 0.1% at 25 °C (except 0.3% for Hellemans *et al.*^{V47}). These deviations are of the same order as the experimental uncertainty. Differences of the viscosity for 1 atm (1.01325×10^5 Pa) and for 1 bar (1×10^5 Pa) are much less than 0.01% and can be

Table 13. Comparison of the present correlation with other correlation and selected experimental data (viscosity of air at 20 and 25 °C for 1 atm)

Author(s)	Year	Method	Viscosity at 20 °C (10 ⁻⁶ Pa·s)	Deviation from Eq.(3a)(%)	Viscosity at 25 °C (10 ⁻⁶ Pa·s)	Deviation from Eq.(3a)(%)	Ref.
Experimental							
Bearden	1939	a	18.1920	-0.18			V30
Kestin et al.	1959	b	18.194	-0.17	18.462	-0.03	V42
Kestin et al.	1959	b	18.21	-0.08			V43
Iwasaki et al.	1963	b	18.199	-0.14			V44
Kestin et al.	1964	b			18.451	-0.09	V45
DiPippo et al.	1968	b			18.45	-0.10	V46
Hellemans et al.	1973	b			18.408	-0.33	V47
Matthews et al.	1976	c	18.21	-0.08	18.45	-0.10	V50
Correlation							
TPRC	1975		18.20	-0.14	18.44	-0.15	R6
Stephan et al.	1979		18.09	-0.74	18.32	-0.80	R11
Present study			18.225		18.468		

Method a: rotating cylinder, b: oscillating disk, c: capillary

Table 14. Comparison of the present correlation with other correlation and selected experimental data (thermal conductivity of air at room temperature and for 1 atm)

Author(s)	Year	Method	Temperature (°C)	Thermal conductivity (10^{-3} W/(m·K))	Deviation from Eq. (5a) (%)	Ref.	
Experimental	Fleeter et al.	a	27.5	26.21	-0.11	T32	
			38.85	27.12	+0.15	T33	
			42.85	27.53	+0.58		
Correlation	TPRC	1970	20	25.62	-0.23	R14	
			25	26.00	-0.23		
			Stephan et al.	20	25.64	-0.16	A1
				25	26.01	-0.19	
			Present study	20	25.68		
25	26.06						

Method a: transient hot-wire

neglected. Therefore, it can be concluded that Eq. (3a) is well accommodated to the previous standard values of the viscosity of air listed in Table 13.

On the contrary with the viscosity, no previous standard values have been proposed for the thermal conductivity of air. The thermal conductivity values of air which are considered the most reliable are listed in Table 14. Agreement at $27.5^{\circ}\text{C}^{\text{T32}}$ and $38.85^{\circ}\text{C}^{\text{T33}}$ suggests that Eq. (5a) in this study represents the best knowledge on the thermal conductivity of air at around room temperature. Therefore, we recommend that the calculated values of $25.68 \text{ mW}/(\text{m}\cdot\text{K})$ at 20°C and $26.06 \text{ mW}/(\text{m}\cdot\text{K})$ at 25°C (both for 1 atm; values for 1 bar differ by no more than 0.01%) be used as the standard values for the thermal conductivity of air.

6. Conclusions

The present situation for experimental data on the viscosity and the thermal conductivity of gaseous air in a wide range of temperature and pressure has been summarized. A close analysis and an evaluation of available data revealed the need for new correlations. Thus, selected data were correlated with the equations of the viscosity and the thermal conductivity. The newly correlated equations cover up to 2000 K and up to 100 MPa for both properties.

In the liquid region as well as in the high-temperature and high-pressure regions, it has been shown that reliable experimental data are very scarce.

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Appendix. Comparison of Our Thermal Conductivity Equation with the Equation of Stephan and Laesecke

After the completion of the present study, the authors were informed that Stephan and Laesecke at Stuttgart University were preparing a manuscript on the correlation of the thermal conductivity of air. They kindly allowed the present authors access to the content of their manuscript^{A1} and the following comparison has been made possible.

Figure A1 shows the claimed ranges of validity of the Stephan and Laesecke equation (SL equation) and the authors' equation (KMN equation). In addition to the overlapping range, the SL equation includes the liquid region at low temperatures, while the KMN equation covers the high-temperature gaseous region. As mentioned in Sec. 4.1, only the data of Tsederberg *et al.*^{T26} are available in the liquid region. The KMN equation has also been developed with these data taken into account (see Sec. 4.2). The present authors excluded the liquid region from the range of validity of the KMN equation merely because the uncertainty of the data of Tsederberg *et al.*^{T26} was hardly assessed.

Detailed comparison of the thermal conductivity calculated with the two equations was done and summarized as follows. Figure A2 shows the deviation of the SL equation from the KMN equation at atmospheric pressure up to 1400 K, the high-temperature limit of the SL equation. The deviation is within the estimated uncertainty and is less than 1% in most of the range. In the dense-gas region, excellent agreement can be seen in the range of density 0–300 kg/m³ as shown in Fig. A3, which shows the deviation of isotherms of the SL equation from those of the KMN equation. Although the deviation is everywhere within the estimated uncertainty limit, the largest deviation of about 4% occurs at $\rho = 500$ – 600 kg/m³ on the 200 and 300 K isotherms. As an example of some more details, the 300 K isotherm of the SL equation is shown in Fig. A4. Both equations perfectly fit the selected data sets of Fleeter *et al.*^{T32} and Scott *et al.*^{T33} in the density range 0–300 kg/m³. However, at higher density, the SL equation deviates from the KMN equation, because the former tried to fit also to the data in the liquid region. In the case of the KMN equation, the data in the liquid region were not

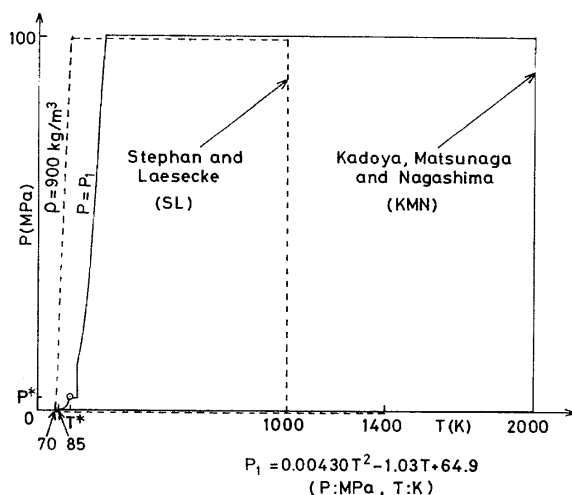


FIG. A1. Regions of validity of the SL and KMN equations.

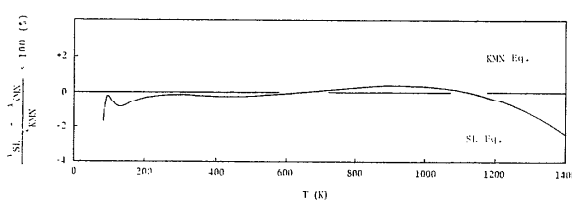


FIG. A2. Comparison of the SL and KMN equations at atmospheric pressure.

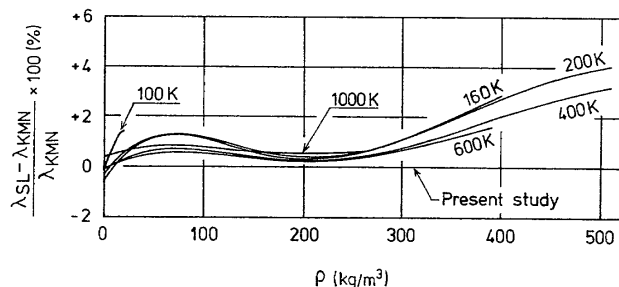


FIG. A3. Comparison of the SL and KMN equations in the dense gaseous region.

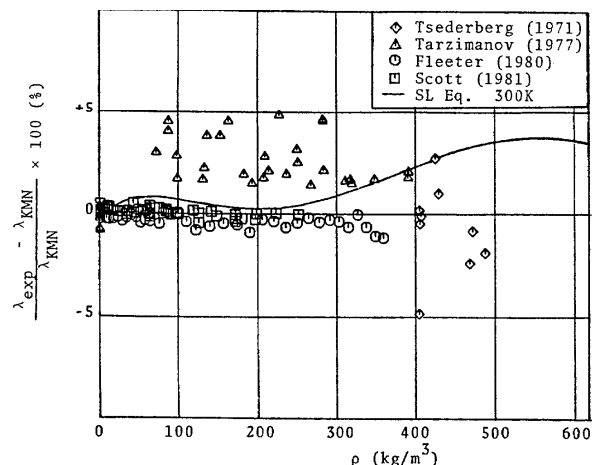


FIG. A4. Comparison of the SL and KMN equations and experimental thermal conductivity at 300 K.

given large weight since the present authors considered that the reliability of the data for the liquid region was far from that of the selected data in the gaseous state.

As a conclusion, the difference between these two independent correlations is smaller than the estimated uncertainty of the correlations, although a discrepancy of up to 4%

exists in a narrow region at lower temperatures and at high densities in the gaseous state.

Reference

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