MEASUREMENT OF THE THERMAL CONDUCTIVITIES OF NEON, KRYPTON, AND XENON OVER A WIDE RANGE OF TEMPERATURES

N. B. Vargaftik and L. V. Yakush

UDC 536.222

The thermal conductivities of certain monatomic gases have been measured at temperatures from 300 to 1200°K and pressures $p \leq 1$ atm. The parameters for the Lennard–Jones (6-12) potential are obtained from the experimental data and used to calculate the viscosities of these gases.

Until recently the experimental data on the thermal conductivities of these gases have been limited to a temperature of 500°C [1, 2]. A somewhat weaker dependence of λ on t was obtained in experiments by Kannuluik and Carman [2]. Recent shock tube experiments at temperatures up to 5000°K are not very accurate; their errors reach 20-30% [3].

We present below the results of measurements of the thermal conductivities of the gases mentioned at temperatures from 300 to 1200°K for $p \approx 1$ atm. Since krypton and xenon have thermal conductivities which are several times smaller than that of air it was necessary to adopt a method of measurement which ensures minimum heat transfer from the heater by radiation at high temperatures. This is best accomplished by using a fine heated wire as in our experiments.

The experimental arrangement is described in [4]. In order to test the reliability of the radiation correction the thermal conductivities of krypton and xenon were measured in two different sized tubes. In the hot wire method λ for the gas is given by the relation

$$\lambda = \frac{Q_\lambda \ln \frac{D}{d}}{2\pi l \Delta t_{\text{gas}}}. \tag{1}$$

The heat transferred per unit time from the heater by radiation is

$$q_{\text{rad}} = \varepsilon\sigma \left[T_1^4 - T_2^4\right] F \approx 4\varepsilon\sigma \Delta T T^3 \pi d l, \tag{2}$$

$$\frac{q_{\text{rad}}}{Q_\lambda} = \frac{2\varepsilon\sigma d \ln \frac{D}{d}}{\lambda} . T^3. \tag{3}$$

Consequently the fraction of the heat transferred by radiation q_{rad}/Q_λ can be significantly decreased by decreasing the diameter d of the central heater and the diameter D of the inner tube. The dimensions of the quartz measuring tubes used in the experiment are as follows:

No. of measuring tube	d, mm	D_{in}, mm	D_{out}, mm	l, mm
I	0.157	4.07	5.69	159.5
II	0.100	2.90	4.01	160

The measuring tube in a quartz sheath was placed vertically in a thermostat whose temperature was kept constant; the temperature difference along the measuring part did not exceed 0.1°C.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 21, No. 3, pp. 491-499, September, 1971. Original article submitted November 10, 1970.

TABLE 1. Experimental Data on λ for Neon

t, °C	W, W	$W_{rad}\cdot 10^3$, W	Δt_{gas}	λ, W/m·deg
36,8	0,2738	0,35	17,55	0,0500
41,0	0,3071	0,47	19,21	0,0507
160,9	0,3621	1,86	18,06	0,0636
168,0	0,4441	2,30	22,0	0,0642
176,6	0,4134	2,90	19,91	0,0654
223,1	0,4905	3,95	22,14	0,0704
250,9	0,5546	6,10	24,13	0,0726
269,4	0,5743	7,09	24,7	0,0735
293,8	0,5362	8,02	22,2	0,0761
427,1	0,6821	18,6	24,0	0,0886
444,4	0,6238	19,7	21,8	0,0912
507,7	0,6550	23,4	21,0	0,0962
604,5	0,7839	43,4	23,2	0,1026
690,0	0,7340	52,2	19,9	0,1100
712,5	1,0086	75,7	26,6	0,1112
800,0	1,0281	93,8	25,0	0,1200

In performing the measurements corrections were made for: 1) the temperature jump; 2) the radiation from the heater; 3) the heat removal from the ends of the heater; 4) the temperature drop in the wall of the measuring tube.

To correct for the temperature jump the experiments were performed at pressures from 50 to 760 mm Hg. This correction was more important for neon, and very small for krypton and xenon. The second correction was made by Eq. (2). The values of ε for platinum were taken from [4]. The correction was larger in experiments with krypton and xenon and therefore the measurements with these gases were performed in two measuring tubes with the ratio q_{rad}/Q_λ differing by a factor of 1.5. The results of the measurements in the two tubes agreed to within 1.5%, which confirms the accuracy of the radiation correction. The correction for heat removal from the ends of the measuring wire was ~1-2%; it was introduced by the method of [4]. The correction for the temperature drop in the wall of the quartz tube is very small for gases; in our measurements it amounted to tenths of a percent of Δt_{gas}.

The central wire located along the axis of the tube is simultaneously the heater and a resistance thermometer. This inside resistance thermometer and the resistance thermometer mounted on the outer surface of the tube were made of Mark PL-1 high-grade platinum wire with $R_{100}/R_0 = 1.3922$. The temperature coefficients α and β of this platinum are known with sufficient accuracy.

Before the experiments were performed the measuring tubes were annealed for 4 h to a temperature of 900°C. The wall temperature was sufficiently accurately determined by the resistance thermometer on

TABLE 2. Experimental Data on λ for Krypton Obtained with Two Measuring Tubes

t, °C	W, W	$W_{rad}\cdot 10^3$, W	Δt_{gas}	λ, W/m·deg
Tube I				
44,7	0,1214	1,16	32,53	0,0103
139,2	0,1949	1,86	45,8	0,0132
224,6	0,2236	10,2	44,99	0,0150
357,6	0,2604	20,9	41,13	0,0184
490,8	0,2898	37,8	37,25	0,0214
572,2	0,3049	50,8	35,1	0,0229
688,7	0,4036	90,9	39,3	0,0253
740,4	0,2992	73	27,12	0,0265
810,8	0,6043	180,5	48,36	0,0279
856,3	0,6284	205,8	46,6	0,0288
880,0	0,6120	207,6	44,75	0,0287
Tube II				
41,1	0,1026	0,9	33,4	0,0101
196,8	0,2250	5,69	49,28	0,0146
260,2	0,2438	8,61	46,77	0,0163
274,6	0,3094	11,9	58,43	0,0166
385,5	0,3416	20,7	58,48	0,0191
458,3	0,3599	30,1	51,49	0,0206
496,8	0,3650	35,4	51,56	0,0212
615,4	0,3893	53,7	45,8	0,0242
786,7	0,4229	93,3	39,65	0,0274

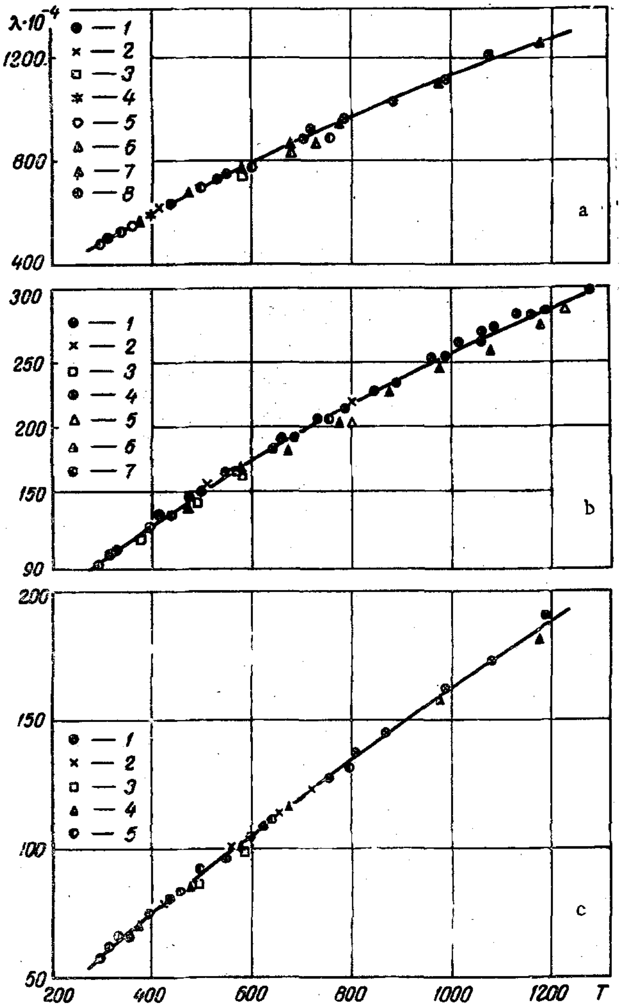

Fig. 1. Thermal conductivities, W/m · deg, of neon (a), krypton (b), and xenon (c), as functions of temperature, °K. Solid curve is calculated. Experimental data: a: 1) our data; 2) [1]; 3) [3]; 4) [7]; 5) [8]; 6) [9]; 7) [10]; 8) [16]; b: 1) our data; 2) [1]; 3) [2]; 4) [12], 5) [13]; 6) [15]; 7) [16]; c: 1) our data; 2) [1]; 3) [2]; 4) [15]; 5) [16].

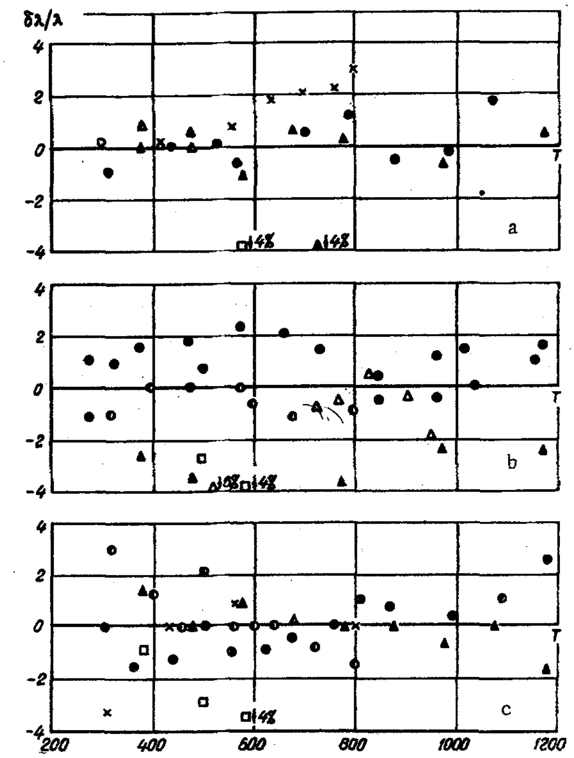

Fig. 2. Comparison of experimental data with calculations according to (5) for: a) neon; b) krypton; c) xenon. Notation as in Fig. 1a, b, c. $\delta\lambda/\lambda$, %; T, °K.

the outside surface of the quartz tube. A 3.5 g weight was suspended from the lower end of the central platinum wire. This produced a certain tension in the wire and affected its resistance. Therefore before and after measuring λ at each temperature the inside resistance thermometer was calibrated with the outside resistance thermometer. This was done by passing a nonheating current I ~ 0.01 A through the thermometers and determining the values of Δt in degrees; these values were taken into account in determining Δt_{gas} [5].

The reference temperature $\bar{t}_{gas}$ is defined as

$$\bar{t}_{gas} = t_{st} + \frac{\Delta t_{gas}}{2}, \qquad (4)$$

where t_{st} is the temperature of the gas at the inner surface of the measuring tube.

The operation of the equipment was tested by repeated measurements of the thermal conductivity of air. The results of these measurements agreed with data in the literature [6] to 1-1.5%. Spectroscopically pure samples of Ne, Kr, and Xe were used in the experiments. The results of the experiments on these gases at temperatures from 30 to 900°C are listed in Tables 1-3. The results for krypton and xenon were obtained with measuring tubes I and II. Our experimental data together with results obtained by others, are shown in Fig. 1a, b, c. We consider first the experimental data of Kannuluik and Carman [2] on the thermal conductivities of all the monatomic gases up to 300°C. The values obtained by Kannuluik and Carman are somewhat lower than ours with a maximum difference of 3-4% at 300°C. They employed the hot wire method with a thick (d = 1.5 mm) platinum heater. In this case the temperature jump was negligibly small, but the correction for heat removal from the ends of the heater, and the radiation correction were considerably increased. For Kr and Xe these corrections amounted to 70-80%. Therefore Kannuluik and Carman were forced to limit their measurements to a temperature of 300°C, although use of a platinum

TABLE 3. Experimental Data on λ for Xenon Obtained with Two Measuring Tubes

t, °C	W, W	$W_{\text{rad}}\cdot 10^3$, W	Δt_{gas}	λ, W/m·deg
Tube I				
25,0	0,0232	0,19	12,59	0,0058
46,1	0,0717	0,56	36,79	0,0061
276,0	0,1151	11,4	34,14	0,0097
400,9	0,1348	21,6	31,45	0,0115
533,4	0,1538	35,7	27,4	0,0137
593,2	0,1615	42,8	26,14	0,0145
693,3	0,2713	91,4	36,9	0,0156
796,5	0,3393	170,8	41,25	0,0173
905,5	0,5375	273,8	144,1	0,0187
Tube II				
82,4	0,1286	0,94	62,78	0,0066
161,5	0,1097	3,8	42,53	0,0080
226,9	0,1216	6,3	41,42	0,0091
348,9	0,1417	12,8	38,86	0,0108
390,5	0,2151	22,9	54,60	0,0115
482,2	0,2315	34,8	50,59	0,0128
606,1	0,2507	55,6	45,1	0,0143
713,6	0,2664	76,6	38,8	0,0162
815,0	0,3045	112,0	36,0	0,0177

heater and a measuring cylinder of platinum–iridium alloy permitted experiments in a higher temperature range.

Experimental values of the thermal conductivity of neon have been reported in [1, 7, 8-10]. All these data agree with our results to within 1-2% for temperatures up to 300°C. For temperatures between 350 and 450°C the difference between our results and those of [9] is 3-5%. Saxena et al. [9] used the method of Blais and Mann [11] to measure the thermal conductivity of neon in the 50-450°C temperature range.

Saxena et al. [9] note that at temperatures above 350°C the thermal processes in the experiments were unstable, and the spread of points reached 10%.

In [10] they give data for higher temperatures. Up to 300°C our results differ from theirs by less than 1% (Fig. 1a). At temperatures from 500 to 900°C these differences increase to 5%. The correction for the temperature jump cannot be determined accurately enough from the experiments. In [10] the estimate of the temperature jump at all temperatures was based on the accomodation coefficient $\alpha = 0.72$ at 25°C. We improved this estimate by taking $\alpha = f(T)$, obtained from our experiments on the thermal conductivity of Ne at various pressures. Our data agree with the refined results of [10] to ~1%. Our total error in determining λ for neon is 2.2%.

Until recently the only data on the thermal conductivity of krypton at high temperatures (up to 1100°C at $p = 250$ and 500 mm Hg) were those of Schafer and Reiter [12]. They did not correct for the temperature jump. It should be noted that this correction is relatively small for krypton, amounting to less than 2% at 1000°C. After introducing this correction the data of Schafer and Reiter on the thermal conductivity of krypton agree with our results to within 1.5% (Fig. 1b). Data on the thermal conductivity of krypton have recently been published by Timrot and Umanskii [13]. The experiments were performed by the method of Blais and Mann. At high temperatures ($t \approx 900$°C) their data agree with our results to within 2%, and at

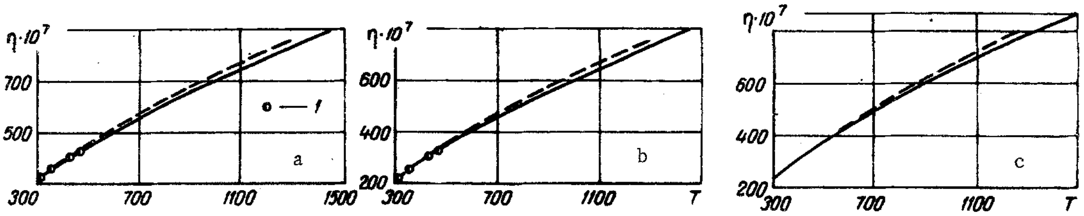

Fig. 3. Viscosity in g/cm · sec as a function of temperature in °K: a) Ne; b) Kr; c) Xe; 1) [17]; continuous curve [18]; open curve calculated with Lennard–Jones (6-12) potential; parameters ε/k and σ: Ne) $\varepsilon/k = 80$°K, $\sigma = 2.551$ Å; Kr) $\varepsilon/k = 228$°K, $\sigma = 3.450$ Å; Xe) $\varepsilon/k = 293$°K, $\sigma = 3.789$ Å.

TABLE 4. Smoothed-Out Values of λ for Neon, Krypton, and Xenon

T, °K	Neon, λ, W /m·deg	Krypton, λ, W /m·deg	Xenon, λ, W /m·deg	T, °K	Neon, λ, W /m·deg	Krypton, λ, W /m·deg	Xenon, λ, W /m·deg
300	0,0494	0,0097	0,0058	800	0,0971	0,0218	0,0135
350	0,0547	0,0111	0,0067	850	0,1012	0,0228	0,0142
400	0,0598	0,0124	0,0075	900	0,1052	0,0238	0,0149
450	0,0649	0,0137	0,0083	950	0,1091	0,0248	0,0156
500	0,0698	0,0149	0,0090	1000	0,1129	0,0258	0,0163
550	0,0747	0,0162	0,0098	1050	0,1166	0,0267	0,0169
600	0,0794	0,0174	0,0106	1100	0,1202	0,0275	0,0176
650	0 0839	0,0185	0,0113	1150	0,1236	0,0284	0,0182
700	0,0884	0,0196	0,0121	1200	0,1269	0,0292	0,0188
750	0,0928	0,0207	0,0128	1250	0,1302	0,0299	0,0194
				1300	0,1333	0,0307	0,0200

moderate temperatures ($t \approx 500°C$) to within 5%, which is within the limits of error of their measurements. Measurements of the thermal conductivities of krypton and xenon at temperatures up to 1200°C have been reported quite recently [15]. The data on krypton systematically diverge from ours by 4%. The values of λ reported in [15] for krypton are lower than ours and lower than those of [12]. Our total error in determining λ for krypton is 2.7%.

Our values of the thermal conductivity of xenon agree with the results of others [1, 14] to within 1-2%. Our values of the thermal conductivity of xenon are in good agreement with the data of [15], the difference amounting to 1-2% except at 900°C where it is 4%.

Our total error in determining λ for xenon is 2.8%.

On the basis of our experimental results and those of others [7-10, 12-16], and taking account of the above indicated corrections to the experiments of Schafer and Reiter [12] and Saxena et al. [10, 15], the following equation is proposed for the thermal conductivity at $p \leq 1$ atm:

$$\lambda = a + bT + cT^2. \tag{5}$$

The coefficients in this equation, obtained by the method of least squares, are: for neon $a = 0.01534$, $b = 0.01204 \cdot 10^{-2}$, $c = -0.02284 \cdot 10^{-6}$; for krypton $a = 0.899 \cdot 10^{-3}$, $b = 0.313 \cdot 10^{-4}$, $c = -0.64 \cdot 10^{-8}$; for xenon $a = 0.649 \cdot 10^{-3}$, $b = 0.1794 \cdot 10^{-4}$, $c = -0.2343 \cdot 10^{-8}$.

In Fig. 2a, b, c the experimental data is compared with calculations according to Eq. (5). The mean deviation of the experimental data is ±2% for Ne, and ±2.5% for Kr and Xe. The smoothed-out values of the thermal conductivities of neon, krypton, and xenon for temperatures up to 1300°C calculated by Eq. (5) are given in Table 4.

Using these data the parameters of the Lennard–Jones (6-12) potential were found to have the following values: for neon $\varepsilon/k = 80°K$, $\sigma = 2.551$ Å; for krypton $\varepsilon/k = 228°K$, $\sigma = 3.450$ Å; for xenon $\varepsilon/k = 314°K$, $\sigma = 3.710$ Å. Using these parameters the coefficients of viscosity of neon, krypton, and xenon were calculated for $T = 273\text{-}1300°K$.

Kestin and Ki Pippo have performed experiments on Ne and Kr at temperatures up to ~500°K. Early in 1970 two new papers on the viscosity of monatomic gases were published. In the first of these Dawe and Smith [18] reported measurements up to 1500°K by the capillary method. In the second Kestin and Kalelkar [19] made measurements on Kr up to 1150°K by the oscillating disk method. The results of [18] and [19], obtained by different methods, agreed to within 1% for krypton.

As is clear from Fig. 3, there is satisfactory agreement between the calculated and measured values of viscosity. The maximum differences at the highest temperatures are $\delta\eta = 2\%$ for neon, 2% for Kr, and 6% for Xe. These differences lie within the limits of the total experimental errors for viscosity and thermal conductivity. The data for Xe show a somewhat greater divergence at the highest temperatures ($T > 1000°K$).

If the experimental data on λ and η are taken into account in choosing the parameters of the Lennard–Jones (6-12) potential $\varepsilon/k = 293°K$ and $\sigma = 3.798$ Å. With these parameters the maximum difference between the measured and calculated values of λ and η for xenon is 3%.

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