VISCOSITY OF MONATOMIC GASES AT TEMPERATURES UP TO 5000-6000°K

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On the basis of analysis of experimental data on the thermal conductivity of monatomic gases at high temperatures and the use of relations from the kinetic-molecular theory, theoretical equations are obtained for the viscosity of the gases up to 5000-6000°K at atmospheric pressure.

The viscosity of monatomic gases has now been studied experimentally up to temperatures on the order of 2000°K [1-23]. There is significant deviation among the results obtained in different studies at high temperatures, this discrepancy being considerably in excess of the experimental error indicated by the authors. This fact was the reason for conducting new studies of the viscosity of these gases at high temperatures. It was found in the 1960s in [5, 7] that the initial high-temperature data on the viscosity of the gases [1-4] was in error: it was lower than the results of newer studies and the error increased with an increase in temperature — reaching 10% for argon at 2000°K, for example.

In recent years objective criteria have been developed for selecting the most reliable data on the viscosity and thermal conductivity of monatomic gases. These criteria are based on the postulates of the kinetic-molecular theory developed by Champion and Cowling and were detailed in the monograph [24]. According to this theory, there exists the following simple relation between the viscosity coefficient η and the thermal conductivity λ of monatomic gases

$$[\eta_k] = 3.207\cdot 10^{-5} M\,[\lambda_k]\, f_\eta^k / f_\lambda^k, \tag{1}$$

where $[\eta_k]$, P · sec and $[\lambda_k]$, W/m · K represent the k-th approximation of the viscosity coefficient and thermal conductivity; M is the molecular weight; f_λ^k and f_η^k are correction factors for the first approximation in the k-th approximation of the viscosity coefficient and thermal conductivity. The value of f_λ^k/f_η^k depends on the character of interaction of the atoms and is close to unity. For example, with a change in the corrected temperature $T^* = kT/\varepsilon$ in the range from 1 to 400, for a Lennard-Jones potential of (12-6), f_λ^3/f_η^3 changes from 1.0001 to 1.0046. Considering that the error of the test data on η at high temperatures is on the order of 0.5% or more and that for λ with an increase in temperature from 300 to 6000°K it increases from 1.5 to 6%, we write Eq. (1) in the form

$$\eta = 3.207\cdot 10^{-5} M\lambda, \tag{2}$$

where λ is the experimental value of thermal conductivity in SI units.

The studies [25-27] presented results of generalization of test data on the thermal conductivity of all monatomic gases at temperatures up to 5000-6000°K. Here, we examined test data obtained by different methods, including the shock-tube method. In analyzing the data, we were able to discover the reason for the systematic discrepancy between the results at temperatures of 1000-2700°K obtained by classical methods and the shock-tube method. This allowed us to match up all of the empirical results obtained for the thermal conductivity of monatomic gases in all of the temperature ranges investigated. It was established that at high temperatures the dependence of thermal conductivity λ on temperature can be represented by the below exponential law for all of the monatomic gases within certain temperature ranges

$$\lambda = AT^m, \tag{3}$$

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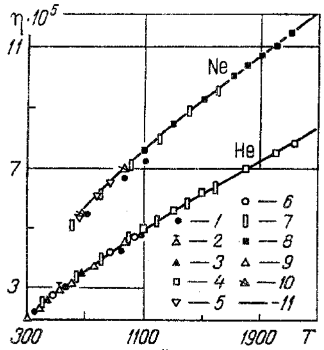

Fig. 1

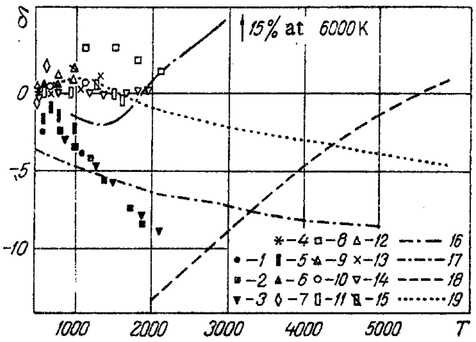

Fig. 2

Fig. 1. Viscosity of helium and neon according to data from various sources: 1) [1]; 2) [5]; 3) [7]; 4) [10]; 5) [11]; 6) [12]; 7) [13]; 8) [16]; 9) [18]; 10) [19]; 11) [4] η, ρ · sec; T, K.

Fig. 2. Deviation of $\delta = (\eta - \eta_{st})/\eta_{st}$, %, from the viscosities of argon calculated from exponential equation (4) for the following data: 1) [1]; 2) [2]; 3) [3]; 4) [5]; 5) [6]; 6) [7]; 7) [9]; 8) [10]; 9) [11]; 10) [12]; 11) [13]; 12) [19]; 13) [20]; 14) [21]; 15) [23]; 16) [28]; 17) [29]; 18) [30]; 19) [33].

TABLE 1. Constants of Eqs. (3) and (4) and the Temperature Ranges for Calculating Thermal Conductivities and Viscosity Coefficients of Monatomic Gases

Gas	A, 10^{-3} W · m^{-1}·K$^{-(m+1)}$	B, 10^{-7} Pa · sec · K^{-m}	m	T, K
Helium	2,649	3,401	0,710	300—6000
Argon	0,4056	5,196	0,675	500—6000
Neon	1,424	9,217	0,630	600—5000
Krypton	0,2112	5,676	0,690	700—5000
Xenon	0,1340	5,642	0,690	800—5000

where A and m are constants for a given gas.

It is interesting, using Eq. (2), to obtain values of the viscosity coefficients of monatomic gases in the temperature range for which empirical data on thermal conductivity is available. Theoretical equations of the following form were obtained for the viscosity of monatomic gases

$$\eta = BT^m. \tag{4}$$

Table 1 shows the constants A, B, and m of Eqs. (3) and (4) and the temperature ranges in which these equations are valid.

Figure 1 shows the available empirical findings on the viscosity of helium and neon at high temperatures. It is apparent that the viscosity values of helium and neon calculated by Eq. (4) (the solid lines in the figure) agree well with new, adequately reliable test results throughout the investigated temperature range [5, 7, 10-13, 16-19]. A similar picture is seen for the other monatomic gases [5-23]. Thus, Eq. (4) may be valid for calculating viscosity at higher temperatures as well, where empirical data exists on heat conductivity.

Figures 2-5 show the deviations of the viscosity coefficients for all of the monatomic gases from the values calculated with Eq. (4). The coefficients in this case were obtained both from experimental data [1-23] and from theoretical results calculated by different methods for a broad range of temperatures [28-34].

It is apparent from the figures that the results of the initial works [1-4] studying viscosity in the high-temperature region proved to be too low. Also too low were the results of the generalizations in [35, 36], which were based on the data from the initial studies [1-4].

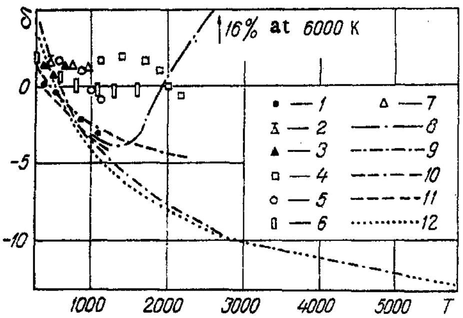

Fig. 3

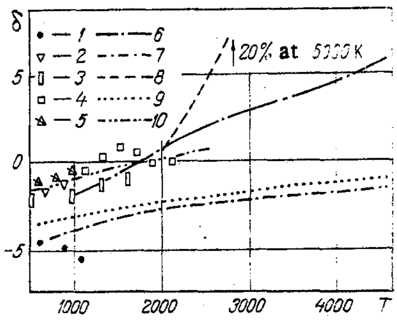

Fig. 4

Fig. 3. Deviation of $\delta = (\eta - \eta_{st})/\eta_{st}$, %, from the viscosities of helium calculated from exponential equation (4) for data from: 1) [1]; 2) [5]; 3) [7]; 4) [10]; 5) [12]; 6) [13]; 7) [18]; 8) [28]; 9) [29]; 10) [35]; 11) [36]; 12) [33].

Fig. 4. Deviation of $\delta = (\eta - \eta_{st})/\eta_{st}$, %, from viscosities of neon calculated from exponential equation (4) for data from: 1) [1]; 2) [11]; 3) [13]; 4) [16]; 5) [19]; 6) [28]; 7) [29]; 8) [30]; 9) [33]; 10) [34].

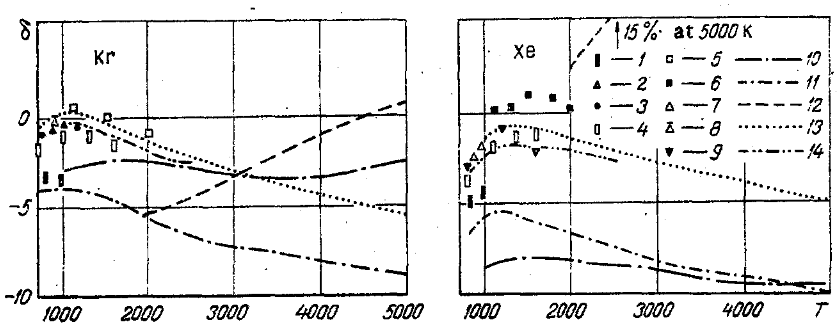

Fig. 5. Deviation of $\delta = (\eta - \eta_{st})/\eta_{st}$, %, from viscosities of krypton and xenon calculated from exponential equation (4) for data from: 1) [6]; 2) [11]; 3) [12]; 4) [13]; 5) [14]; 6) [15]; 7) [17]; 8) [19]; 9) [23]; 10) [28]; 11) [29]; 12) [31]; 13) [33]; 14) [34].

TABLE 2. Viscosity of Monatomic Gases η, 10^{-5} P · sec, at Atmospheric Pressure

T, K	He	Ar	Ne	Kr	Xe	T, K	He	Ar	Ne	Kr	Xe
300	1,95					2500	8,79	10,2	12,7	12,5	12,5
400	2,39					2600	9,04	10,5	13,1	12,9	12,8
500	2,80	3,45				2700	9,29	10,8	13,4	13,2	13,1
600	3,19	3,90	5,18			2800	9,52	11,0	13,7	13,6	13,5
700	3,56	4,33	5,71	5,21		2900	9,77	11,3	14,0	13,9	13,8
800	3,91	4,73	6,22	5,72	5,68	3000	10,0	11,5	14,3	14,2	14,1
900	4,26	5,12	6,69	6,20	6,16	3200	10,5	12,1	14,9	14,9	14,8
1000	4,59	5,50	7,15	6,67	6,63	3400	10,9	12,6	15,4	15,5	15,4
1100	4,91	5,87	7,60	7,12	7,08	3600	11,4	13,1	16,0	16,1	16,0
1200	5,22	6,22	8,02	7,56	7.52	3800	11,8	13,5	16,6	16.7	16,6
1300	5,53	6,57	8,44	7,99	7,94	4000	12,3	14,0	17,1	17,3	17,2
1400	5,83	6,91	8,84	8,41	8,36	4200	12,7	14,5	17,7	17,9	17,8
1500	6,12	7,24	9,24	8,82	8,77	4400	13,1	15,0	18,2	18,5	18,4
1600	6,40	7,56	9,62	9,22	9,17	4600	13,6	15,4	18,7	19,1	19,0
1700	6,69	7,87	9,99	9,62	9,56	4800	14,0	15,9	19,2	19,7	19,6
1800	6,96	8,18	10,3	10,0	9,94	5000	14,4	16,3	19,7	20,2	20,1
1900	7,24	8,49	10,7	10,4	10,3	5200	14,8	16,7			
2000	7,50	8,79	11,1	10,8	10,7	5400	15,2	17,2			
2100	7,77	9,08	11,4	11,1	11,1	5600	15,6	17,6			
2200	8,03	9,37	11,7	11,5	11,4	5800	16,0	18,0			
2300	8,29	9,66	12,1	11,8	11,8	6000	16,4	18,4			
2400	8,54	9,94	12,4	12,2	12,1						

New high-temperature experimental data [5-23] on the viscosity of the monatomic gases, obtained by different methods, agrees with Eq. (4) generally to within 1-3%. This makes it possible to evaluate the error of the viscosity values shown in Table 2 and calculated from Eq. (4) as 3% up to 2000°K and, allowing for the error of the data on heat conduction, as 6% in the range 5000-6000°K.

The generalized results on the viscosity of monatomic gases presented in the handbook literature [37-42] for the temperature range in question deviates from Eq. (4) by 1-3%. Viscosities obtained theoretically for high temperatures on the basis of test data on the scattering of atomic beams by gas targets [28, 30, 31] deviates 10-20% from Eq. (4), except for krypton. The deviation for the latter is on the order of 5%.

The widely known data of Svehla [29] lies below the results obtained with Eq. (4) by 5-10%. Calculations were performed in [29] with the relations of the kinetic-molecular theory using parameters of the Lennard-Jones potential (12-6). These calculations, also based on the understated viscosity values in [1-4], were performed for the temperature range 800-2000°K and temperatures up to 5000°K.

Theoretical values of viscosity coefficients up to 2000-2100°K in [23] agree well with Eq. (4). The calculated results in [33] deviate from Eq. (4) by about 5% at 5000-6000°K for all of the monatomic gases except helium. Here, the deviation is 13% at 6000°K.

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