EXPERIMENTAL STUDY OF THERMAL CONDUCTIVITY OF NEON–HELIUM MIXTURES AT HIGH TEMPERATURES

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UDC 536.23

Experimental data on the thermal conductivity of neon–helium mixtures in the temperature range 350-1500°K are presented. Above 800°K these are the first such experimentally obtained data.

The study of the thermal conductivity of monatomic gases and their mixtures over a wide temperature range is of significant interest for the development and refinement of theory, while also having major practical importance.

Knowledge of the thermophysical characteristics of monatomic gases and their mixtures is necessary in gas-laser construction in order to calculate heat flow from cathode to anode, from the sections forming the capillary channel and to design heaters, etc.

The temperature dependence of the thermal conductivity of neon–helium mixtures has been studied inadequately [4], and at temperatures below 0°C no data are available. The range 273-363°K has been studied most thoroughly, but even there the majority of authors measured the thermal conductivity of the He–Ne mixture at one of two definite temperatures [5-9, 12], i.e., the concentration dependence of thermal conductivity of the given mixture was studied. In [10] the hot-wire method was used for the first time to study the temperature dependence of thermal conductivity of an He–Ne mixture at three concentrations (0.2566, 0.4560, and 0.7552Ne) in the temperature range 303-363°K to an accuracy of ±2%. Saxena and Tondon [11] presented smoothed and interpolated thermal-conductivity values from [10] for neon–helium mixtures (0.2, 0.4, 0.6, and 0.8Ne).

In [9], the thermal conductivity of an He–Ne mixture was measured by the hot-wire method at two temperatures – 302 and 793°K – to an accuracy of ±2%. This was the first experimental measurement at a significantly high temperature. The experimental thermal-conductivity values of the He–Ne mixture at 302°K in [9] are systematically higher than the experimental data of [10, 11] (Fig. 1) (mean deviation comprises 3.6%).

The thermal conductivity of an He–Ne mixture was first measured by the hot-wire method in 1953 at a temperature of 273°K [5, 6]. The authors of [5, 6] obtained an empirical equation for calculation of the concentration dependence of thermal conductivity. The values calculated with this equation differ from experiment by ±1.2%. In [7, 8] the thermal conductivity of this mixture at 291°K was studied with a katharometer calibrated with the then-available data on the thermal conductivity of argon–helium mixtures [13]. The measurement uncertainty was not presented, but comparison shows that the data of [7, 8] are significantly higher in value than the results of others. The present authors used graphical correlation to smooth and interpolate the values of [7, 8], demonstrating that for the four mixtures (0.2, 0.4, 0.6, and 0.8Ne) the value lie an average of 9% above those of [10, 11], upon which the correlation at these temperatures was based [2]. In [12], the thermal conductivity of an He–Ne mixture was first studied at a temperature of 297.1°K by the nonstationary cylindrical-probe method with a linear heat source (the technique, theory, and apparatus are described in detail in [14]). As for the experimental data of [12], they are systematically low in comparison with other data. The mean deviation for the four mixtures comprises not less than 14% [2].

On the basis of the above, it may be concluded that at the present time the thermal conductivity of neon–helium mixtures has not been studied sufficiently even in the room-temperature range. The thermal-conductivity of the pure gases helium and neon has been studied by the authors previously [1, 3]. In determining the thermal conductivity of the neon–helium

A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 34, No. 6, pp. 1020-1026, June, 1978. Original article submitted May 3, 1977.

0022-0841/78/3406-0685$07.50

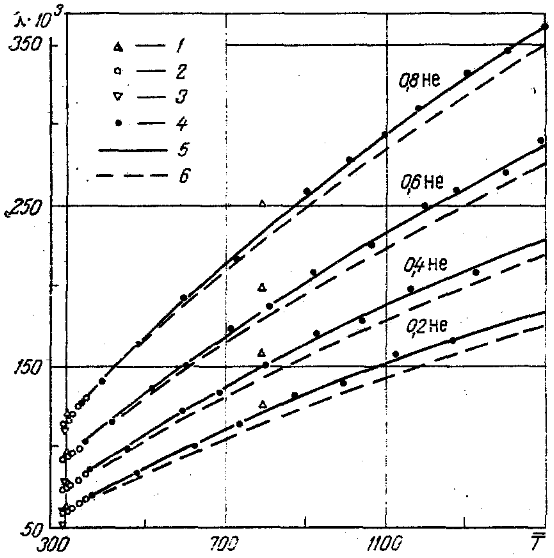

Fig. 1

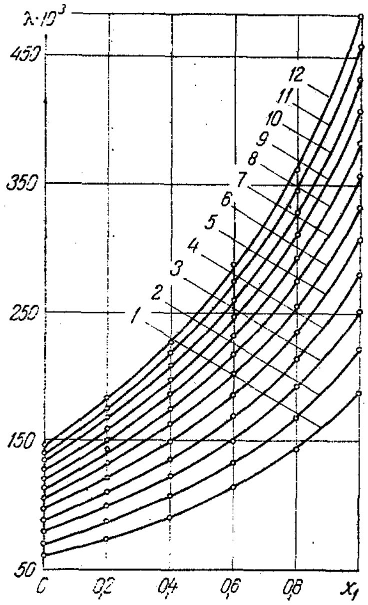

Fig. 2

Fig. 1. Temperature dependence of thermal conductivity of neon–helium mixtures: 1) data of [9]; 2) [10]; 3) [12]; 4) experiment; 5, 6) results of present study [5) smoothed values; 6) calculation (exp–6)]; $\lambda \cdot 10^3$, W/m•°K; $\bar{T}$, °K.

Fig. 2. Concentration dependence of thermal conductivity of neon–helium mixtures at "rounded" temperature values: 1) 400°K; 2) 500; 3) 600; 4) 700; 5) 800; 6) 900; 7) 1000; 8) 1100; 9) 1200; 10) 1300; 11) 1400; 12) 1500°K.

mixtures, all factors which distort the true value of the measured quantity were considered, as described in [2]. Therefore, we will dwell only on the corrections which have the most significant effects at high temperatures. For the heaviest of the mixtures studied (0.8Ne–0.2He), the radiation correction increased with temperature from tenths of a percent at 365°K to 8.5% at 1265°K. The correction for temperature shift was determined experimentally over the entire temperature range of 350–1500°K and the pressure range 100 mbar to 1 bar. The largest correction for temperature shift was observed in the case of the lightest mixture (0.2Ne–0.8He), comprising ~24% at T = 1502°K. It should be noted that for all the neon–helium mixtures studied the absolute value of the temperature-shift correction is greater than that for radiation (Table 1). This is explained by the fact that neon–helium mixtures are the lightest of all mixtures of monatomic gases.

Figure 1 shows the thermal-conductivity data obtained in the present study for the temperature range 350–1500°K at a pressure of 1 bar. The mixtures were prepared from high-purity helium (99.993%) with the following impurity content (in percent): neon, 0.002; hydrogen, 0.002; nitrogen, 0.002; oxygen, 0.0005; and hydrocarbons, 0.0005. The neon used was of 99.882% purity with hydrogen content 0.001%; helium, 0.1%; oxygen, 0.001%; nitrogen, 0.01%; and moisture not more than 0.02 g/cm³.

The thermal conductivity of the mixtures (0.2, 0.4, 0.6, and 0.8Ne) were measured over different temperature ranges: 336–1502, 349–1493, 359–1326, and 365–1265°K. The 0.2Ne–0.8He mixture was thus studied over the widest range, while the range of study of the 0.8Ne–0.2He was the narrowest (with a maximum temperature of 1265°K).

The experimental data obtained can be compared with the single available experimental thermal-conductivity value of [9], obtained at 793°K. The data of [9] are systematically higher as compared to ours (Fig. 1). The deviations for the four mixtures (0.2, 0.4, 0.6, and 0.8Ne) comprise 7.3%, 7.6%, 6.8%, and 4.6%, respectively. The experimental data obtained in the present study "join" quite well with the values of [10, 11] in the moderate temperature range (363°K).

TABLE 1. Measurement Data and Experimental Values of Coefficient of Thermal Conductivity for Neon–Helium Mixtures at p = 1 bar

T_{wa}, °K	T_{wi}, °K	T_g, °K	$\bar{T}$, °K	$Q\cdot10^6$, W	$Q_r\cdot10^6$, W	$Q_c\cdot10^6$, W	$\lambda\cdot10^3$, W/m·°K	δT_{sh}, %
				0,2Ne — 0,8He				
331,7	340,99	9,22	336	107823	54	107775	126	0,8
382,5	391,7	9,08	387	118866	95	118771	141	1,3
475,4	484,49	8,87	480	134352	222	134130	163	2,4
592,3	601,28	8,61	597	153898	536	153362	192	4,1
719,5	728,38	8,36	724	169441	1147	168294	217	5,8
893,8	902,54	7,87	898	191791	2694	189097	259	9,9
1003,8	1012,48	7,57	1008	199472	4237	195235	278	12,8
1094,9	1103,55	7,40	1098	207144	6007	201137	293	14,5
1177,5	1186,13	7,16	1181	213977	8057	205920	310	17,0
1298,5	1307,10	6,92	1302	225585	11812	213773	333	19,5
1404,0	1412,59	6,69	1407	231768	16126	215642	347	22,1
1499,2	1507,76	6,51	1502	240551	21038	219513	363	24,0
				0,4Ne — 0,6He				
344,1	354,6	10,41	349	99538	70	99468	103	0,9
406,7	417,16	10,31	412	109117	140	108977	114	1,4
505,8	516,19	10,13	511	126750	331	126419	135	2,5
594,0	604,35	9,97	599	139476	625	138851	150	3,7
706,1	716,42	9,78	711	159115	1248	157867	174	5,2
804,2	814,5	9,60	809	168656	2114	166542	187	6,8
910,6	920,87	9,33	915	183490	3455	180035	208	9,2
1057,0	1067,22	8,97	1061	194257	6201	188056	226	12,2
1191,3	1201,49	8,66	1196	210788	9949	200839	250	15,0
1268,4	1278,57	8,50	1273	217019	12779	204240	259	16,5
1396,9	1407,03	8,24	1401	225927	18762	207165	271	18,7
1488,5	1498,61	8,07	1493	242809	24207	218602	292	20,2
				0,6Ne — 0,4He				
353,4	364,63	11,13	359	87952	86	87866	85,1	0,9
447,9	459,09	11,01	453	100526	222	100304	98,2	1,6
583,3	594,44	10,77	589	122523	630	121893	122	3,3
679,0	690,11	10,63	684	132305	1152	131153	133	4,3
797,1	808,17	10,41	802	148017	2190	145827	151	6,0
917,7	928,72	10,13	923	162619	3799	158820	169	8,1
1034,9	1045,88	9,85	1040	169128	6104	163024	178	10,3
1155,0	1165,94	9,60	1160	185515	9453	176062	198	12,2
1321,6	1332,47	9,22	1326	194965	16198	178767	209	15,2
				0,8Ne — 0,2He				
358,6	370,7	12,00	365	77137	100	77037	69,2	0,9
471,5	483,55	11,85	477	91423	290	91133	82,9	1,7
618,6	630,60	11,59	624	108377	858	107519	100	3,4
730,1	742,07	11,41	736	121276	1665	119611	113	4,7
865,7	877,64	11,19	871	139283	3298	135985	131	6,3
988,5	1000,40	10,92	994	146388	5575	140813	139	8,2
1117,4	1129,25	10,69	1123	165683	8997	156686	158	9,8
1259,5	1271,30	10,33	1265	172082	14546	157546	164	12,5

The experimental values obtained in the present study were compared with theoretical values calculated using the formulas of strict molecular-kinetic theory [15] with various potential functions [Lennard-Jones, Buckingham (exp–6), and Morse] and corresponding potential parameters (Table 2). The divergence among calculated values obtained with the various potential functions is insignificant. The theoretical thermal-conductivity values obtained with the Lennard-Jones (12–6) potential function with potential parameters from [16] are slightly higher than those of [15], in the temperature range of 400–1500°K, i.e., closer to the experimental data for all mixtures (0.2, 0.4, 0.6, and 0.8 Ne), being higher by average amounts of 0.5%, 1.0%, 1.4%, and 1.8%, respectively. The best agreement (Fig. 1) appears between our experimental data and the theoretical values calculated with the modified Buckingham potential (exp–6) with potential parameters from [17]. However, in this case also, one must note that the calculated values, like those obtained with the Lennard-Jones (12–6) potential, lie systematically lower than the experimental data for all mixtures studied. The divergence between experimental and theoretical values increases with decrease in the content of the lighter component (helium) in the mixture and with increase in temperature (Table 3). For the mixtures with 0.6 and 0.8He, the divergence does not exceed the error limit of ±4%, but for the 0.4He and

TABLE 2. Potential-Function Parameters for Interaction of Similar and Dissimilar Molecules

Mixture	Potential function	Variant	ε_1/k, °K	ε_2/k, °K	ε_{12}/k, °K	σ_1, Å	σ_2, Å	σ_{12}, Å	α_1	α_2	α_{12}	Reference
He — Ne	(12 — 6)	I	10,22	35,7	19,101	2,576	2,789	2,6825	—	—	—	[15]
	(12 — 6)	II	11,29	45,58	21,12	2,556	2,707	2,644	—	—	—	[16]
	(exp — 6)	I	9,16	38,0	18,71	3,135	3,147	3,143	12,4	14,5	13,46	[17]
	Morse	I	8,55	67,1	24,0	2,687	2,611	2,643	6,0	8,0	7,0	[18]

TABLE 3. Comparison of Smoothed and Interpolated Experimental Thermal-Conductivity Values for Neon—Helium Mixtures with Theoretical Values Calculated Using Modified Buckingham (exp—6) Potential ($\lambda \cdot 10^3$, W/m·°K)

T, °K	x_1 = 0,2 exp.	0,2 theory	0,4 exp.	0,4 theory	0,6 exp.	0,6 theory	0,8 exp.	0,8 theory
400	73,8	71,8 +2,8%*	91,3	89,4 +2,1%	113	113	143	143
500	87,2	83,5 +4,4%	107	104 +2,9%	133	131 +1,5%	168	168
600	98,9	94,5 +4,7%	122	118 +3,4%	150	149 +0,7%	192	190 +1,0%
700	110	105 +4,8%	136	131 +3,8%	168	165 +1,8%	214	211 +1,4%
800	121	115 +5,2%	150	143 +4,9%	185	181 +2,2%	235	231 +1,7%
900	132	124 +6,4%	163	155 +5,2%	202	196 +3,1	255	250 +2,0%
1000	142	133 +6,8%	175	166 +5,4%	217	210 +3,3%	275	267 +3,0%
1100	151	142 +6,3%	187	178 +5,0%	232	224 +3,6%	293	285 +2,8%
1200	159	151 +5,3%	198	188 +5,3%	247	237 +4,2%	311	301 +3,3%
1300	168	159 +5,7%	208	199 +4,5%	260	250 +4,0%	328	318 +3,1%
1400	175	167 +4,8%	218	209 +4,3%	274	263 +4,2%	345	334 +3,3%
1500	183	175 +4,6%	227	210 +3,7%	287	276 +4,0%	361	350 +3,1%

*$[(\lambda_{exp} - \lambda_{theory})/\lambda_{theory}] \cdot 100\%$ — deviation of experimental data from theoretical data.

especially for the 0.2He mixture, the deviation exceeds the experimental uncertainty by 2.5-3%. This can be partially explained, in our opinion, for deviations up to 1-1.5% by the fact that at low helium concentrations (0.2He) impurities in the gases studied affect the results more strongly, especially helium in the neon (0.1%). We have reached this conclusion by studying the concentration dependence of the thermal conductivity in He—Ne mixtures (Fig. 2).

It should also be noted that the theoretical values obtained with the Morse potential and potential parameters from [18] lie somewhat below the calculated values obtained with the Buckingham (exp—6) potential.

By analyzing the concentration dependence of the thermal conductivity of an He—Ne mixture over the wide temperature range of 400-1500°K (Fig. 2), we have concluded that the amount of deviation of the concentration isotherms from a linear law is practically independent of temperature for an equimolar mixture.

We had arrived at analogous conclusions previously for argon—helium [2] and argon—neon [3] mixtures. The previous study also offers an explanation of this deviation. For an equimolar He—Ne mixture, this deviation is of the order of 17.8%.

Comparison of experimental and theoretical thermal-conductivity values for binary mixtures of the light monatomic gases (He–Ne, Ne–Ar) has shown that the modified Buckingham (exp–6) potential is the one most suitable for calculation of thermal-conductivity coefficients. However, in both cases, at all concentration levels (0.2, 0.4, 0.6, and 0.8Ne), the theoretical values lie below experimental ones. In our opinion, this may be partially explained by nonconsideration of the dependence of the potential parameters themselves on temperature and by a certain imperfection in the combination rules for calculation of potential parameters for interaction of dissimilar molecules.

NOTATION

T_{wa}, temperature of molybdenum tube wall, °K; T_{wi}, temperature of measurement wire, °K; ΔT_g, true temperature shift in gas layer, °K; $\overline{T}$, mean temperature, °K; Q, effective thermal flux, W; Q_c, Q_r, thermal fluxes transmitted by conduction and radiation, respectively, W; δT_{sh}, correction for temperature shift, %; λ, thermal conductivity of gas mixture, W/m·°K; ε_i, σ_i, ε_{ij}, σ_{ij}, potential-function parameters for intermolecular interaction of similar and dissimilar molecules, respectively; α, slope of exponential repulsion term; x_1, concentration of lighter component (He).

LITERATURE CITED

1. E. I. Marchenkov and A. G. Shashkov, Inzh.-Fiz. Zh., 26, No. 6 (1974).
2. E. I. Marchenkov, Author's Abstract of Candidate's Dissertation, A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk (1975).
3. E. I. Marchenkov and V. I. Aleinikova, Inzh.-Fiz. Zh., 33, No. 5 (1977).
4. A. G. Shashkov and E. I. Marchenkov, in: Studies of the Thermophysical Properties of Materials [in Russian], Izd. ITMO, Akad. Nauk BelorusSSR, Minsk (1971), p. 15.
5. I. M. Davidson and I. M. Music, U. S. Atomic Energy Commission HW-29021, 7 (1953).
6. G. A. Gook et al., Interscience Publications, 1, New York (1961).
7. W. A. D. Baker, Master's Dissertation, University of London (1955).
8. E. Thornton and W. A. D. Baker, Proc. Phys. Soc., 80, Part 5, 1171 (1962).
9. H. Ubisch, Ark. Fys. 16, No. 1, 93 (1959).
10. I. M. Gandhi and S. C. Saxena, Mol. Phys., 12, No. 1, 57 (1967).
11. S. C. Saxena and P. K. Tondon, in: Proceedings of the Fourth Symposium on Thermophysics (1968), p. 398.
12. H. L. Burge and L. B. Robinson, J. Appl. Phys., 39, No. 1 (1968).
13. J. Wachsmuth, Phys. Z., 9, No. 7, 235 (1908).
14. A. G. Shashkov and E. I. Marchenkov, in: Problems of Heat and Mass Transfer [in Russian], Énergiya, Moscow (1970), p. 297.
15. J. O. Hirschfelder, C. F. Curtiss, and R. B. Bird, Molecular Theory of Gases and Liquids, Wiley (1964).
16. J. Kestin et al., Physica, 58, No. 2, 165 (1972).
17. E. A. Mason, J. Chem. Phys., 23, 49 (1955).
18. O. P. Bahethi et al., Z. Naturforsch., 19a, 1478 (1963).