THERMAL CONDUCTIVITY OF HELIUM IN THE RANGE 400-1500°K AS DETERMINED BY A MOLYBDENUM MEASUREMENT CELL

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The apparatus described uses a heated wire (filament) to heat a molybdenum measurement cell by passage of electric current. The thermal conductivity of helium is measured in the range 400-1500°K with maximum experimental error of ±4%.

Experimental studies of the thermal conductivity of monatomic gases and their mixtures are of great interest for the purpose of further developing the mathematical theory of inhomogeneous gases of Chapman and Cowling [15, 16, 17].

Development of new technological processes also requires a knowledge of thermal conductivity with sufficient accuracy over wide temperature intervals. The thermal conductivity of monatomic gases above 1000°K has been measured infrequently, and there are few experimental studies thereon [18]. Moreover, the temperature range 1000-2000°K is also of special interest, because at higher temperatures thermal conductivity is usually determined by shock tube methods, whose methodology is based on use of the values of thermal conductivity within this range. Accuracy of data obtained by shock tube methods is low, of the order of ±15-20%. To study thermal conductivity within the interval 400-1500°K the present study employed an apparatus using the heated wire (filament) method, with the special feature that the measurement cell constructed of molybdenum was heated by passage of an electric current.

A schematic diagram of the apparatus is shown in Fig. 1, with the measurement cell depicted in Fig. 2.

Tube 6 is prepared from vacuum smelted molybdenum, type MChVP. Tube length is 300 mm, internal diameter 5.7 mm, and wall thickness 0.3 mm. To obtain a temperature stabilized region in the center of the tube about 150 mm long, end screens with heaters 5 and coaxial cylindrical screens 3 are used. The temperature drop over the working section of the tube in our experiments did not exceed 0.5-1°C. Heater power was 500 W. The maximum power of 1 kW was supplied to the tube at a temperature of 2000°K.

Measurement wire 1 was prepared from MR-50 molybdenum alloy, 0.1 mm in diameter. The resistivity, coefficient of radiation, and ratio of resistance to resistance at 293°K of the wire as functions of temperature were determined in special experiments using the apparatus of Vertogradskii [1]. The error in determining the resistance ratio, to a reliability of 95%, was no more than 0.3%.

The wire and tube were cleaned and annealed using electrovacuum techniques [14]. The diameter of the wire and external diameter of the tube were measured with a UIM-21 microscope to an accuracy of ±0.001 mm. The length of the working sections of the wire was determined with a UZA-2 comparator to an accuracy of ±0.001 mm. The internal diameter of the tube was determined indirectly by filling it with water. Tube diameter was then calculated from liquid volume. Tungsten conductors (VR-20) of diameter 0.05 mm with aluminum oxide insulation were used for the three potential leads. Centering bushing 11 and collar 8 were made of ceramic material.

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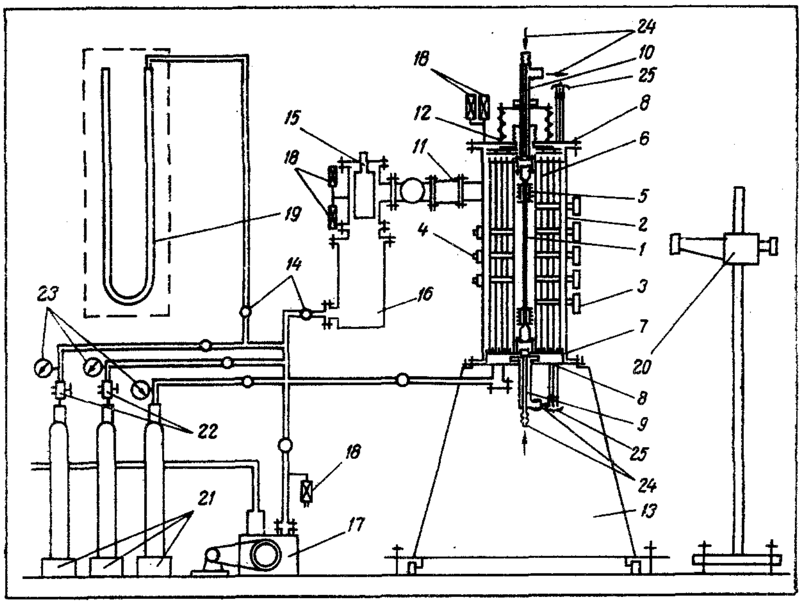

Fig. 1. Schematic diagram of measuring apparatus: 1) measurement cell; 2) cooled chassis; 3) observation openings; 4) openings for testing gas mixture; 5) end screens with protected heaters; 6) cylindrical screens; 7) screen supports; 8) cooled cover; 9) fixed lower current lead; 10) movable upper current lead; 11) bellows; 12) spring; 13) chassis support; 14) vacuum valves; 15) trap; 16) diffusion vacuum pump; 17) VN-2NG vacuum pump; 18) vacuumetric lamp; 19) U-shaped vacuum meter; 20) pyrometer; 21) gas cylinders; 22) pressure regulator; 23) vacuum meters; 24) cooling system; 25) measurement system.

The measurement wire was assembled with an I020.0002M welder system, used in instrumentation and electronics industries. A platinum foil 0.02 mm in thickness was used as a substrate in welding the tungsten–rhenium wires. The wire was axially loaded by tungsten springs 12. These springs ensured constant tension on the measurement wire over the entire temperature range for the duration of the experiment. Eccentricity of the wire and quality of the assembly were checked after mounting by x-raying in two perpendicular planes with an RUP-200 x-ray apparatus. A second check of eccentricity was made in a similar manner after performing measurements.

The tube (experimental cell) was heated by passage of a stabilized ac current. An ST 2000.4 electronic regulator maintained the voltage at the input of an RNO-250-2A regulated autotransformer constant to within ±0.2%. The voltage from the output of the RNO-250-2A was applied to the tube through a step-down transformer. A rheostat was connected in the high voltage winding circuit for fine adjustment of the current through the tube. The maximum current reached a value of ~200 A. The system provides high quality high reliability electrical contacts.

The protected end heaters were fed independently from a source of stabilized ac voltage. Accurate regulation of heater current was done with rheostats. The heaters were made of tungsten rhenium wire (VR-20) 0.3 mm in diameter with aluminum oxide insulation.

The molybdenum tube was mounted in molybdenum holders, which were connected to the cooled current leads by intermediate molybdenum tubes. The lower current lead 9 (Fig. 1) was fixed, while the upper was adjustable, allowing for compensation for thermal expansion of the molybdenum tube. The movable contact is connected to the body by a bellows, tensioned by springs 12. The observation windows 3 permit observation during heating and measurement of the tube temperature by pyrometer 20.

In the temperature range where there is no radiation from the tube, control of temperature distribution over the tube length is done by three platinum–rhodium thermocouples PR 30/6.

The wire is fed direct current from a type BP-591-86 power supply. The wire current is measured by a milliammeter, and controlled by a resistance box and fine adjustment rheostat from the ÉOP-66

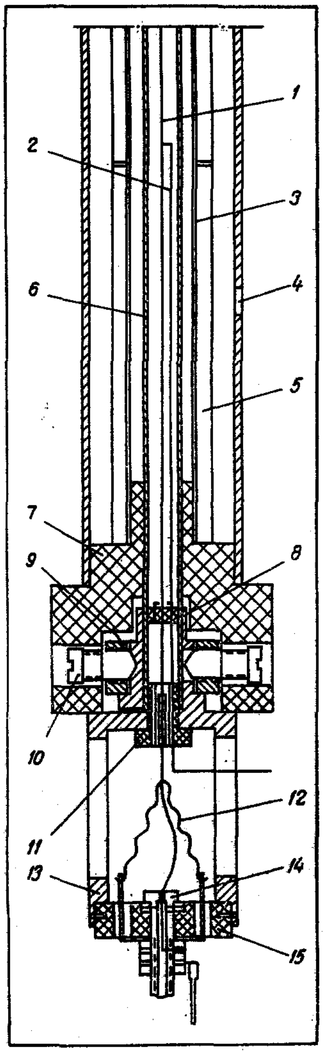

Fig. 2. Measurement cell: 1) wire; 2) potential lead; 3) molybdenum screen; 4) observation opening; 5) protected heater; 6) molybdenum tube; 7) end screen; 8) centering collar; 9) ring; 10) mounting screws; 11) bushing; 12) tungsten spring; 13) molybdenum holders; 14) measurement wire current lead; 15) collar.

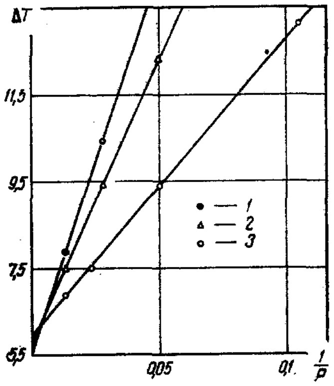

Fig. 3. The function $\Delta T = f(1/P)$ for determination of correction for temperature differential at various temperatures: 1) T = 1413°K; 2) 1216; 3) 932. ΔT, °K; 1/P, cm^{-1} Hg.

pyrometer. The current value is measured by the potentiometer method to an accuracy of ±0.01 mA.

The measurement system allows determination of the resistances of the long R_l and short R_s sections of wire to an accuracy of $\pm 10^{-4}$ Ω. Resistance was measured for two directions of "nonheating" current $I_0 = 2$ mA, with an R-330 potentiometer. The wire was heated by a current of the order of I = 250 mA and measurements were made with an R-307 potentiometer. In helium at atmospheric pressure this gave a temperature differential of about 6-8°K.

Tube temperature was controlled by the pyrometer, measured (by resistance thermometer) by the wire itself with the "nonheating" current, and maintained constant over the course of measurements.

Temperature distribution over the measurement section of the tube was determined by the pyrometer and three thermocouples, installed at the center and both ends of this section. Device output in a stable mode continued for 4-5 h.

The vacuum system (Fig. 1) consisted of an N-5S-M1 oil vapor pump 16, a VN-2MG prepump 17, and a nitrogen trap 15. In the device chamber 2 a vacuum of the order of $1 \cdot 10^{-4}$ mbar was attained. Cleaning and degasification of the chamber, measurement cell, and insulation screen were performed with the vacuum system after assembly.

TABLE 1. Experimental Data and Experimental Values of Helium Thermal Conductivity at P = 1 atm (I_0 = 0.002 A; I = 0.250 A)

R_l^0	R_s^0	R_l	R_s	$\frac{R_{ef}^0}{R_{ef}^{20}}$	$\frac{R_{ef}}{R_{ef}^{20}}$	T_{wall}	ΔT	T_{wall}	ΔT_{gas}	$\bar{T}$	$Q \cdot 10^6$	$Q_r \cdot 10^6$	$Q_c \cdot 10^6$	$\lambda \cdot 10^3$	$\frac{\lambda - \lambda_{[3]}}{\lambda_{[3]}} \cdot 100\%$
2,7515	0,9965	2,7735	1,0044	1,1730	1,1825	404,6	5,9	410,5	5,8	407*	110562	75	110487	191	2,7
3,4440	1,2434	3,4672	1,2517	1,4709	1,4809	600,5	6,2	606,7	5,9	603	138460	380	138080	253	0,8
4,6605	1,6770	4,6852	1,6853	1,9942	2,0051	928,5	6,9	935,4	6,0	932	187482	2444	185038	332	—1,8
5,6774	2,0394	5,7044	2,0492	2,4316	2,4432	1213,7	7,4	1221,1	5,8	1216	228435	7593	220842	410	0,3
6,3741	2,2828	6,4013	2,2925	2,7346	2,7463	1409,8	7,8	1417,6	5,6	1413	256778	14744	242034	465	1,5

* Mean temperature rounded to whole degrees.

Before performing the experiments the apparatus was evacuated for 8-10 h with subsequent heating and passage of the gas to be studied through all gas lines for 20-30 min. Then only chamber and measurement cell were filled with gas. Gas purity was checked with an indicator lamp with filaments prepared of measurement wire material. The lamp filament temperature was measured with the pyrometer. The absence of a deposit on the lamp envelope indicated that the gas did not interact with the filament. The apparatus was filled with gas through regulator 22, pressure being measured by a type MBP manometer to an accuracy of ±0.05 mbar.

Body, cover, and current leads were cooled by water. During the time of the experiment their temperature was maintained constant to within ±0.1°.

The constants characterizing the measurement cell were as follows: internal tube diameter $d_2 = 5.700 \pm 0.005$ mm; external tube diameter D $= 6.300 \pm 0.001$ mm; measurement wire diameter $d_1 = 0.100 \pm 0.001$ mm; length of long portion of wire $l_l = 92.965 \pm 0.001$ mm; length of short portion of wire $l_s = 33.139 \pm 0.001$ mm; resistance of long portion of wire at 20°C $R_l^{20} = 2.3248 \pm 0.004\ \Omega$; resistance of short portion of wire at 20°C $R_s^{20} = 0.8287 \pm 0.002\ \Omega$; effective length $l_{ef} = l_l - l_s = 59.826 \pm 0.002$ mm; effective resistance at 20°C $R_{ef}^{20} = R_l^{20} - R_s^{20} = 1.4961 \pm 0.0003\ \Omega$.

The method described in [2] was used to process the experimental results. In our apparatus heat transfer is excluded by device geometry, since over the entire temperature range considered the Rayleigh number is less than 1000 [3]

In order to avoid correction by computation for heat loss from the wire ends, a wire with three potential leads was used, and the experimental method itself provided the correction [4].

The eccentricity in our experiment was 0.2 mm and produces a correction in the thermal conductivity value of 0.2%. The temperature drop in the wall of the molybdenum tube is negligibly small.

Correction for temperature differential was introduced experimentally, using the relationship of [5]

$$\Delta T = B\left(\frac{1}{P}\right) + \Delta T_{gas}. \tag{1}$$

If the thermal flux produced by thermal conductivity through the gas layer studied is held constant, then the temperature difference between wire and wall will change linearly with the quantity 1/P, according to [1] (Fig. 3). In experiments with different values of 1/P the wire resistance and the value of current passed through it were changed. These changes, opposite in sign, compensate each other, so that the thermal flux varied little.

The change in thermal flux produced by conductivity is somewhat greater at high temperatures, since radiant flux then plays an important role, changing more rapidly with change from one pressure to another due to the sharp change in wire temperature. In this case maintenance of a constant thermal flux is somewhat more complicated. Measurements were made at three different pressures: 1050, 500, and 150 mbar.

The temperature difference between wire and wall was calculated with the formula of [2]:

$$\Delta T = \frac{R_{ef} - R_{ef}^0}{R_{ef}^{20} \frac{d}{dT}\left(\frac{R_{ef}^{T}}{R_{ef}^{20}}\right)}. \tag{2}$$

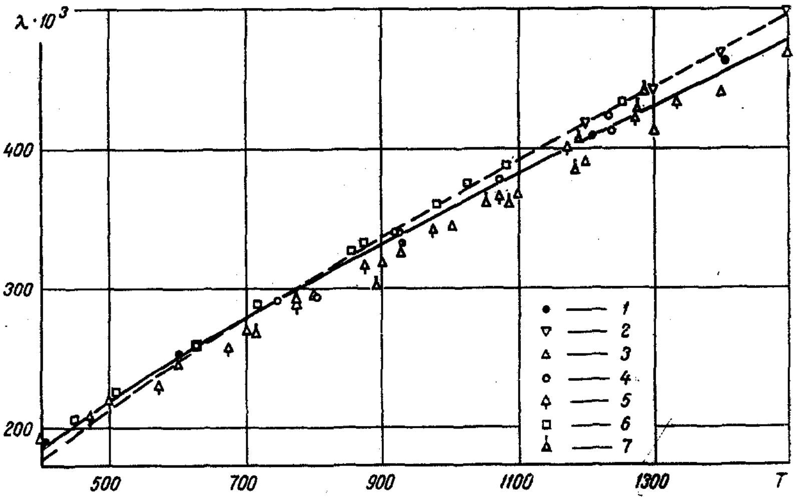

Fig. 4. Comparison of data on thermal conductivity of helium with [3] and [6] in the temperature range 400–1500°K. Solid line) [3]; dashes) [6]. 1) Present data; 2) [7]; 3) [8]; 4) [9]; 5) [10]; 6) [11]; 7) [12]; λ, W/m·deg; T, °K.

The heat transmitted by radiation was calculated with the formula:

$$Q_r = c_p \left[\left(\frac{T_{wire}}{100} \right)^4 - \left(\frac{T_{wall}}{100} \right)^4 \right] \pi d_1 l_{ef}. \tag{3}$$

The amount of heat liberated by the wire was determined by

$$Q = I^2 R_{ef} - I_0^2 R_{ef}^0. \tag{4}$$

Then the heat transmitted by conduction through the gas will be

$$Q_c = Q - Q_r. \tag{5}$$

The thermal conductivity of the gas was then found with the expression

$$\lambda = A \frac{Q_c}{\Delta T_{gas}}, \tag{6}$$

where $A = \ln(d_2/d_1)/2\pi l_{ef}$.

The coefficient of thermal conductivity for the gas obtained with Eq. (6) is related to the mean temperature

$$\bar{T} = T_{wall} + \frac{\Delta T_{gas}}{2}. \tag{7}$$

Thus, with the apparatus developed the thermal conductivity of helium was studied over the temperature range 400–1500°K. The experiments used high purity (99.993%) helium with the following impurity content: hydrogen 0.002; nitrogen 0.002; oxygen 0.0005; hydrocarbon 0.0005; neon 0.002%.

Table 1 presents the results of the measurements. Uncertainty in the thermal conductivity values obtained is ±4%. The greatest contribution to this uncertainty is produced by the error connected with measurement of the temperature difference in the gas layer, which is ±2.5%.

In Fig. 4 the data of the present experiments are compared with those of [3] and [6], which are recommended as standards. Also shown are experimental data from [7–12], in which helium thermal conductivity was studied above 1000°K.

The maximum deviation of our data from that of [3] occurs at 407°K and comprises 2.7%. Above 1000°K the point scattering is less than ±2% and indicates good agreement of our data and that of [3].

Comparison with the results of [6] shows that our values differ somewhat more than in the case of [3]: at 407°K our data are higher by 4.9%, and at 1413°, lower by 1.5%. A study of the data of [6] reveals that they do not lie on a smooth curve over the entire temperature range. This explains the greater divergence of our data from that of [6].

Also to be noted are the experimental results of [10], obtained up to 1333°K and not included in the correlations of [3] and [6], with uncertainty of ±2%.

Our data were obtained at temperatures up to 1413°K, i.e., they encompass a wide temperature range and agree well with the values of [10].

It can be concluded from the above that the values of [10] and our experimental data are the closest to the true values of thermal conductivity at temperatures above 1000°K and that the standard values of [3] agree better with the more accurate data of [10] and with our experimental values, than do the recommended results of [6].

NOTATION

d_1	is the diameter of the measurement wire, mm;
d_2	is the inner tube diameter, mm;
D	is the outer tube diameter, mm;
l_l	is the length of the long segment of wire, mm;
l_s	is the length of the short segment of wire, mm;
R_l^{20}	is the resistance of the long wire segment at 20°C, Ω;
R_s^{20}	is the resistance of the short wire segment at 20°C, Ω;
l_{ef}	is the effective length, mm;
R_{ef}^{20}	is the effective resistance at 20°C, Ω;
I_0	is the "nonheating" current, A;
I	is the "heating" current, A;
R_l^0	is the resistance of the long wire segment with "nonheating" current, Ω;
R_s^0	is the resistance of the short wire segment with "nonheating" current, Ω;
R_1	is the resistance of the long wire segment with "heating" current, Ω;
R_s	is the resistance of the short wire segment with "heating" current, Ω;
R_{ef}^0	is the effective resistance with "nonheating" current, Ω;
R_{ef}	is the effective resistance with "heating" current, Ω;
T_{wall}	is the temperature of the molybdenum tube wall, °K;
T_{wire}	is the temperature of the measurement wire, °K;
ΔT	is the temperature difference between the wire and the wall, °K;
ΔT_{gas}	is the true temperature differential in the gas layer, °K;
$\bar{T}$	is the mean temperature, °K;
Q	is the effective heat liberated by the measurement wire, W;
Q_c	is the heat transferred by conductivity, W;
B	is the quantity dependent on the wire material, physical properties, measurement cell geometry, and thermal flux, deg · mbar;
P	is the gas pressure, mbar;
$d/dT(R_{ef}^T/R_{ef}^{20})$	is the temperature derivative of the ratio of the effective wire resistance to effective resistance at 20°C, deg^{-1};
c_p	is the emissivity of the wire, $W/m^2 \cdot deg^4$;
λ	is the thermal conductivity of the gas, W/m · deg;
Q_r	is the quantity of heat transmitted by radiation, W.

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