THERMAL CONDUCTIVITY OF HELIUM AT TEMPERATURES OF 0-1000°C AND PRESSURES OF 1-200 ATM

(UDC 621.039.534.3)

N. B. Vargaftik and N. Kh. Zimina

Translated from Atomnaya Energiya, Vol. 19, No. 3, pp. 300-303, September, 1965

Original article submitted December 21, 1964; in revised form, May 14, 1965

A number of studies published in recent years have been concerned with the thermal conductivity \( \lambda \) of helium over a wide range of temperatures and pressures [1-7]. However, the results of experiments conducted by various authors are not in sufficiently good agreement, and this makes it difficult to determine the behavior of the function \( \lambda = f(t, p) \).

The purpose of the present study is the experimental investigation of the thermal conductivity of helium in the 0-1000°C temperature range at a pressure of 1 atm, as well as an analysis of published experimental data on the thermal conductivity of this gas at various values of \( t \) and \( p \). The investigations were conducted on the apparatus described in [8], using the hot-wire method. (The methods used for the calculations and for processing the experimental data are described in the same reference.)

In the processing of the experimental data, it is particularly important to make a correction for the temperature jump, since at high temperatures the value of the correction for helium is considerable, even at \( p = 1 \) atm, as will be shown below.

As is known [9], the correction for the temperature jump is calculated by means of the formula

\[
\Delta t = \Delta t_{\text{gas}} + B \left( \frac{1}{p} \right),
\]

where \( \Delta t \) is the measured temperature drop between the wire and the inner surface of the measuring-tube wall; \( \Delta t_{\text{gas}} \) is the actual temperature drop in the gas layer; \( B \) is a value dependent on the physical properties of the gas and the wire material, as well as on the geometry of the instrument and the total amount of heat, \( Q \), generated by the wire.

Thus, \( \Delta t \) must be linear function of 1/p when \( Q \) = const. From the measured values of \( \Delta t \) corresponding to different pressures at the same average gas temperature, we can construct the linear function \( \Delta t = f(1/p) \). By extrapolating \( \Delta t \) to the value 1/p = 0, we can find the value of \( \Delta t_{\text{gas}} \) which appears in the basic formula for determining the thermal conductivity \( \lambda \) of a gas by the hot-wire method:

\[
\lambda = A \frac{Q}{\Delta t_{\text{gas}}},
\]

where \( A \) is a constant depending on the instrument. For a given gas pressure and specified conditions of temperature and instrument geometry, the temperature-jump correction \( \Delta t_J \) can be found by the formula

\[
(\delta t_J)_p = \frac{\Delta t_p - \Delta t_{\text{gas}}}{\Delta t_p},
\]

where the subscript \( p \) represents the gas pressure for which the correction is determined.

Fig. 1. Graph of \( \Delta t = f(1/p) \) for various values of temperature: 1) 355°C; 2) 652°C; 3) 962°C.
TABLE 1. Experimental Values of the Thermal Conductivity of Helium at $p = 1$ atm

| No. of experimental points | $t$, °C | $Q$, cal/hour | $Q_{rad}$, cal/hour | $Q_{end}/Q$, % | $\Delta t_{gas}$, °C | $\lambda \times 10^6$ cal/ \(\text{cm} \cdot \text{sec} \cdot \text{°C}^{\circ})$
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>37</td>
<td>228.7</td>
<td>0.2</td>
<td>4.1</td>
<td>5.42</td>
<td>371</td>
</tr>
<tr>
<td>2</td>
<td>414</td>
<td>410.1</td>
<td>0.7</td>
<td>4.1</td>
<td>8.21</td>
<td>442</td>
</tr>
<tr>
<td>3</td>
<td>123</td>
<td>693.0</td>
<td>1.3</td>
<td>4.1</td>
<td>13.43</td>
<td>455</td>
</tr>
<tr>
<td>4</td>
<td>354</td>
<td>569.6</td>
<td>4.0</td>
<td>1.08</td>
<td>8.19</td>
<td>620</td>
</tr>
<tr>
<td>5</td>
<td>355</td>
<td>893.5</td>
<td>6.4</td>
<td>1.08</td>
<td>12.77</td>
<td>617</td>
</tr>
<tr>
<td>6</td>
<td>472</td>
<td>649.2</td>
<td>7.8</td>
<td>1.08</td>
<td>8.19</td>
<td>695</td>
</tr>
<tr>
<td>7</td>
<td>684</td>
<td>1424.1</td>
<td>16.9</td>
<td>1.08</td>
<td>17.80</td>
<td>703</td>
</tr>
<tr>
<td>8</td>
<td>645</td>
<td>875.2</td>
<td>19.6</td>
<td>1.08</td>
<td>9.27</td>
<td>843</td>
</tr>
<tr>
<td>9</td>
<td>652</td>
<td>1472.0</td>
<td>33.7</td>
<td>1.08</td>
<td>15.60</td>
<td>813</td>
</tr>
<tr>
<td>10</td>
<td>802</td>
<td>953.8</td>
<td>35.2</td>
<td>1.08</td>
<td>8.95</td>
<td>900</td>
</tr>
<tr>
<td>11</td>
<td>962</td>
<td>1517.5</td>
<td>93.6</td>
<td>1.08</td>
<td>12.35</td>
<td>1012</td>
</tr>
<tr>
<td>12</td>
<td>965</td>
<td>1524.0</td>
<td>98.0</td>
<td>1.08</td>
<td>12.65</td>
<td>989</td>
</tr>
</tbody>
</table>

Notation: $Q = \text{total heat generated by the wire}; Q_{rad} = \text{amount of heat produced by radiation per unit time}; t = \text{average gas temperature}; \Delta t_{gas} = \text{actual temperature drop in gas layer}; Q_{end}/Q = \text{fraction of heat removed through the ends of the wire}.$

For each temperature value, we conducted experiments at four different pressures: 760, 360, 200, and 110 mm Hg. From these values we constructed the functions $\Delta t = f(1/p)$ in order to determine $\Delta t_{gas}$ (Fig. 1). Table 1 shows the experimental results we obtained. The maximum experimental error is 1.5% in the 0-600°C range and 2.0% in the 600-1000°C range. In Fig. 2 these results are compared with the data of other authors. It can be seen that the results of the present study are in good agreement with the data of [2-4, 6]. The data of [1] are not shown in Fig. 2. The authors conducted their experiments with monatomic gases for pressures of $p = 350-760$ mm Hg, and in this pressure range they ignored the correction for the temperature jump, which is especially large for a light gas (helium). Unfortunately, [1] does not mention the exact values of the gas pressure, and consequently it is impossible to take exact account of the influence of the temperature jump.

The work of Johannin et al. [6] on the thermal conductivity of helium is of special interest. The measurements were made by the coaxial-cylinder method (the gap between the silver cylinders was 0.2 mm) at temperatures of 30-356°C and pressures of 1-200 atm. This reference compares the experimental data with the results calculated by the Enskog formula for the thermal conductivity of compressed gases [10]:

$$\lambda = \lambda_0 \left(\frac{1}{Y} + 1.2 + 0.755Y\right),$$

where $\lambda$ is the thermal conductivity of the compressed gas; $\lambda_0$ is the thermal conductivity of the gas in the ideal gas state; $\rho$ is the density of the gas. For hard spherical molecules the value of $Y$ is determined from the formula

$$Y = b_0 + 0.625(b_0)^2 + 0.287(b_0)^3 + 0.115(b_0)^4,$$

Here $b_0 = (2/3)N_0r_m^2$ is the second virial coefficient for hard spheres, where $N_0$ is Avogadro's number and $r_m = 3.22$ Å [6].

The values of $\rho$ were taken from [11], in which these values are given for rounded-off values of the temperature $t$ in °C. The authors of [6] therefore interpolated their experimental data on $\lambda$; the two extreme isotherms corresponded to 37.8°C and 315.6°C (100°F and 400°F). Figure 3 shows the experimental results and those calculated by