Thermal expansion of vanadium in the temperature range of 98–2400 K

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Abstract. The experimental results of a study of the thermal expansion of polycrystalline vanadium in the temperature range of 98–1723 K are presented. The correlation of the dilatometric data and γ-ray attenuation technique was established. The temperature dependence of thermal properties up to 2400 K was obtained and reference table of recommended values was calculated.

1. Introduction
An analysis of experimental data on the thermal expansion of vanadium, performed in major reviews [1, 2] shows a significant discrepancy between the existing results. For this reason, the estimated error of the data recommended in [1] for the relative expansion of vanadium above 298 K is 5%, and below it is 10%. Therefore, the data require verification and refinement using modern experimental equipment.

The purpose of this work is to measure the linear thermal expansion coefficient (LTEC) of polycrystalline vanadium in a wide range of solid-state temperatures and to obtain the recommended values of thermal properties up to 2400 K, taking into account the data performed by γ-ray attenuation technique [3].

2. Method and experimental equipment
LTEC measurements were carried out by dilatometric method on the DIL-402C (NETZSCH, Germany) setup using fused silica and corundum holders. The sample expansion was recorded with an inductive displacement transducer (LVDT) with a resolution of up to 0.125 nm, and the temperature was measured with thermocouples (S or E type depending on the temperature range). The heating–cooling rate of the furnace was 2 K/min. Measurements were carried out in a helium atmosphere (99.995 vol.%).

The experimental technique is described in detail in [4]. The setup is tested under identical conditions on samples of aluminium (99.99 wt. %) and platinum (99.93 wt. %). The analysis shows that the difference between the obtained and reference data [5, 6] is within 3%.

3. Results and Discussion
The experiments were performed on a cylindrical sample of vanadium (VNM-1). The sample was obtained by machining initial material with a purity of 99.3 mass. %.
Thermal expansion was measured in seven heating–cooling cycles in the temperature range of 98–1723 K. Results showed good reproducibility, which allowed combining data from different cycles. The generalized temperature dependence of the LTEC is shown in figure 1. To obtain smoothed curves, initial data were fitted by the least squares method using Shomate equation [7]:

$$\alpha(T) = 10.255 + 2.277 \times 10^{-3} T - 2.551 \times 10^{-6} T^2 + 1.646 \times 10^{-9} T^3 - 612.9 T^{-1}$$

(1)

where $T$ is the temperature in K, and the dimension $\alpha$ is $10^{-6}$ K$^{-1}$. The random approximation error (95% confidence probability) of the LTEC didn’t exceed 0.5%, and the total is 2–4%. The smoothed values of the thermal coefficients of linear and volume expansion ($\beta$), relative expansion ($\varepsilon$) and density ($\rho$) are presented in table 1. Density at room temperature is taken from [3].

![Figure 1. Initial data of the vanadium LTEC.](image)

| $T$ (K) | $\alpha$ ($10^{-6}$ K$^{-1}$) | $\beta$ ($10^{-5}$ K$^{-1}$) | $\varepsilon$ ($10^{-6}$) | $\rho$ (kg m$^{-3}$) |
|--------|-------------------------------|-----------------------------|------------------------|---------------------|
| 100    | 4.33                          | 1.30                        | -1390                  | 6099                |
| 120    | 5.39                          | 1.62                        | -1293                  | 6098                |
| 140    | 6.15                          | 1.85                        | -1177                  | 6096                |
| 160    | 6.73                          | 2.02                        | -1048                  | 6093                |
| 180    | 7.19                          | 2.16                        | -908                   | 6091                |
| 190    | 7.38                          | 2.22                        | -836                   | 6089                |
| 200    | 7.56                          | 2.27                        | -761                   | 6088                |
| 250    | 8.24                          | 2.47                        | -365                   | 6081                |
| 273.15 | 8.48                          | 2.54                        | -171                   | 6077                |
| 293.15 | 8.65                          | 2.60                        | 0                      | 6074                |
| 300    | 8.71                          | 2.61                        | 59                     | 6073                |
| 350    | 9.06                          | 2.72                        | 504                    | 6065                |
| 400    | 9.33                          | 2.80                        | 964                    | 6057                |
| 500    | 9.74                          | 2.91                        | 1919                   | 6039                |
| 600    | 10.04                         | 3.00                        | 2908                   | 6021                |
| 700    | 10.29                         | 3.07                        | 3924                   | 6003                |
| 800    | 10.52                         | 3.14                        | 4965                   | 5984                |
| 900    | 10.76                         | 3.21                        | 6028                   | 5966                |
| 1000   | 11.01                         | 3.28                        | 7117                   | 5946                |
| 1100   | 11.31                         | 3.36                        | 8232                   | 5926                |
| 1200   | 11.65                         | 3.46                        | 9380                   | 5906                |
| 1300   | 12.05                         | 3.58                        | 10564                  | 5886                |
Table 1. Smoothed values of linear and volume thermal expansion coefficients, relative expansion and density of vanadium.

| T (K) | $\alpha$ ($10^{-6}$ K$^{-1}$) | $\beta$ ($10^{-5}$ K$^{-1}$) | $\varepsilon$ ($10^{-6}$) | $\rho$ (kg m$^{-3}$) |
|-------|-----------------------------|-----------------------------|-----------------|-----------------|
| 1400  | 12.52                       | 3.71                        | 11792           | 5864            |
| 1500  | 13.08                       | 3.87                        | 13071           | 5842            |
| 1600  | 13.73                       | 4.06                        | 14410           | 5819            |
| 1700  | 14.48                       | 4.28                        | 15820           | 5795            |
| 1723$^1$ | 14.67                     | 4.33                        | 16155           | 5789            |
| 1800  | –                           | 4.53                        | 17310           | 5769            |
| 1900  | –                           | 4.81                        | 18893           | 5742            |
| 2000  | –                           | 5.13                        | 20583           | 5714            |
| 2100  | –                           | 5.50                        | 22392           | 5684            |
| 2172$^2$ | –                           | 5.79                        | 23777           | 5661            |
| 2172$^2$ | –                           | 8.27                        | –               | 5453            |
| 2200  | –                           | 8.29                        | –               | 5441            |
| 2300  | –                           | 8.36                        | –               | 5396            |
| 2400  | –                           | 8.43                        | –               | 5351            |

$^1$ values above 1723 K were obtained using data [3];

$^2$ $T_f$ is melting temperature.

Figure 2. Comparison of our results with the data of other authors. 
1 — [1]; 2 — [2]; 3 — [3]; 4 — the results of this work; 5 — extrapolation using equation (1).
A comparison of our data with recommendations [1, 2] and γ-ray experiment data [3] is shown in figure 2. Our data are between the recommended values from [1] and [2] below 600 K, and above they are lower by 4–8%. It should be noted that the results of our work coincide with the data of [3] within the error of the latter. A noticeable deviation of the LTEC at the room temperature region is obviously related to the «high» lower measurement boundary in [3], which did not allow taking into account the drop of the LTEC below the Debye temperature. At the same time, in the rest of the temperature range, the difference between the data does not exceed the LTEC error [3], including the extrapolation of our data to the melting point ($T_f = 2172$ K). The difference in the relative density change calculated by the equation 1 and γ-ray experimental data from 293 K to $T_f$ does not exceed 0.1%. This provides a basis to construct a vanadium density polytherm in the temperature range of 100–2400 K, for which the data of the LTEC and density in the solid state, as well as of the density in the solid and liquid phases with the measured density change on melting are consistent [3].

**Conclusion**

New experimental data on the linear thermal expansion coefficient of polycrystalline vanadium have been obtained. The correlation of the data performed by dilatometric method and γ-ray attenuation technique has been established. Tables of recommended values of the volumetric properties have been developed.

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