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AN ANALYSIS OF THE EMISSIVE PROPERTIES OF MOLYBDENUM FROM 1000—2000 K

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Abstract: Normal spectral radiance of molybdenum was evaluated according to published emissivity data. From the spectral radiance the reduced curve was obtained and the total radiance, total emissivity, maximum-spectral-radiance wavelength, and maximum-spectral radiance. An empirical formula was found for the wavelength of the maximum spectral radiance.

1. Introduction

An analysis of the emissive properties of molybdenum described here was made analogously to the analysis of tungsten emissive properties[1]. Normal spectral radiance in the wavelength range from 0.4 to 5 μm and for temperatures from 1000 to 2000 K was tabulated (Table 1) using the spectral emissivities measured by Dmitriev and Kholopov[2] who applied two methods for measuring the spectral emissivity. For wavelengths from 0.4 to 1.5 μm they used basically the same design of the source as was used by de Vos[3]; for wavelengths from 0.9 to 5 μm they used a relative method comparing the emissivities with the emissivity which exists for the wavelength of 0.91 μm. (At 0.91 μm molybdenum has what is called an X-point, where the spectral emissivity does not depend on temperature. In this case it was equal to 0.33.)

2. Results

The curves of the spectral radiance were plotted using Table 1, and total radiance $L(T)$, total emissivity $\varepsilon(T)$, maximum-spectral radiance wavelength λ_m and maximum-spectral radiance $L(\lambda_m, T)$ were evaluated (Table 2). Radiance was found to be negligible for wavelengths below 0.4 μm; however, it

Table 1

Normal spectral radiance of molybdenum.

$L(\lambda, T) = p \times 10^{r}$ ($W \cdot cm^{-3} \cdot sr^{-1}$)

Wave-length µm	1000 K		1200 K		1400 K		1600 K		1800 K		2000 K	
	p	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*
0.4	1.30	—6	5.06	—4	3.60	—2	8.77	—1	1.05	1	7.62	1
0.5	5.38	—4	6.39	—2	1.92	0	2.47	1	1.79	2	8.80	2
0.6	2.49	—2	1.33	0	2.27	1	1.90	2	9.91	2	3.70	3
0.7	3.35	—1	1.01	1	1.15	2	7.10	2	2.93	3	8.82	3
0.8	2.08	1	4.14	1	3.48	2	1.72	3	5.92	3	1.55	4
0.9	7.72	0	1.11	2	7.43	2	3.09	3	9.40	3	2.28	4
1.0	2.05	1	2.28	2	1.28	3	4.65	3	1.27	4	2.85	4
1.1	4.19	1	3.81	2	1.86	3	6.08	3	1.54	4	3.21	4
1.2	7.15	1	5.54	2	2.41	3	7.24	3	1.71	4	3.41	4
1.3	1.07	2	7.28	2	2.89	3	8.04	3	1.80	4	3.44	4
1.4	1.44	2	8.84	2	3.24	3	8.52	3	1.81	4	3.34	4
1.5	1.81	2	1.02	3	3.49	3	8.75	3	1.77	4	3.17	4
1.6	2.13	2	1.11	3	3.61	3	8.61	3	1.70	4	2.94	4
1.7	2.42	2	1.18	3	3.64	3	8.31	3	1.59	4	2.72	4
1.8	2.68	2	1.22	3	3.59	3	7.91	3	1.47	4	2.46	4
1.9	2.85	2	1.22	3	3.47	3	7.45	3	1.36	4	2.23	4
2.0	2.98	2	1.21	3	3.32	3	6.95	3	1.24	4	2.00	4
2.2	3.09	2	1.15	3	2.96	3	5.89	3	1.02	4	1.61	4
2.4	3.07	2	1.04	3	2.54	3	4.92	3	8.28	3	1.27	4
2.6	2.95	2	9.49	2	2.20	3	4.08	3	6.73	3	1.02	4
2.8	2.79	2	8.46	2	1.86	3	3.38	3	5.46	3	8.10	3
3.0	2.58	2	7.45	2	1.58	3	2.79	3	4.44	3	6.53	3
3.2	2.37	2	6.53	2	1.34	3	2.32	3	3.64	3	5.25	3
3.4	2.13	2	5.65	2	1.14	3	1.95	3	2.98	3	4.28	3
3.6	1.83	2	4.90	2	9.80	2	1.63	3	2.45	3	3.46	3
3.8	1.71	2	4.29	2	8.32	2	1.37	3	2.03	3	2.86	3
4.0	1.51	2	3.73	2	7.05	2	1.16	3	1.70	3	2.36	3
4.2	1.35	2	3.24	2	5.97	2	9.64	2	1.41	3	1.96	3
4.4	1.18	2	2.79	2	5.12	2	8.21	2	1.19	3	1.63	3
4.6	1.03	2	2.44	2	4.44	2	6.97	2	1.02	3	1.36	3
4.8	9.10	1	2.14	2	3.80	2	6.03	2	8.62	2	1.16	3
5.0	7.98	1	1.87	2	3.30	2	5.15	2	7.45	2	1.00	3

was not negligible for wavelengths exceeding 5 µm. The linear extrapolation made for the spectral radiance curves above 5 µm may partly account for the difference between our total emissivities and those shown in Ref.[2] ($T = 1000$ and 1200 K). With linear extrapolation, radiation above 5 µm amounted to 10 % of the total radiance at 1000 K and 2 % at 2000 K.

The total emissivities are shown in Fig. 1 in comparison with those from different sources. In addition, total emissivity was evaluated according to the Hagen-Rubens relation ($\varepsilon(T) = 0.574 \sqrt{\rho T}$, where ρ ($\Omega \cdot cm$) is the resistivity), and a linear dependence on temperature was found. The resistivity

Table 2

Integral radiance $L(T)$, total emissivity $\varepsilon(T)$, wavelength of maximum spectral radiance λ_m, and maximum spectral radiance $L(\lambda_m, T)$ of molybdenum.

T K	$L(T) = \int L(\lambda, T)\,\mathrm{d}\lambda$ $\mathrm{W \cdot cm^{-2} \cdot sr^{-1}}$	$\varepsilon(T) = \dfrac{\pi L(T)}{\sigma T^4}$	λ_m μm	$L(\lambda_m, T)$ $\mathrm{W \cdot cm^{-3} \cdot sr^{-1}}$
1000	0.085	0.047	2.28	0.031×10^4
1200	0.288	0.073	1.90	0.122×10^4
1400	0.753	0.108	1.69	0.364×10^4
1600	1.615	0.137	1.51	0.875×10^4
1800	3.089	0.163	1.37	1.815×10^4
2000	5.437	0.188	1.28	3.450×10^4

was taken from Ref.[4] (The resistivity also rises proportionally to temperature.) From this we can also evaluate the Wiedeman-Franz constant L using the thermal conductivity[5] which was found constant in the temperature range from 2 200 to 2 900 K and equal to 1.4 ($\mathrm{W \cdot cm^{-1} \cdot K^{-1}}$). Assuming that the thermal conductivity is of the same value at $T = 1723$ K (maximum temperature for the published values of the resistivity[4]), we obtain: $L = 3.7 \cdot 10^{-8}$ ($\mathrm{W \cdot \Omega \cdot K^{-2}}$).

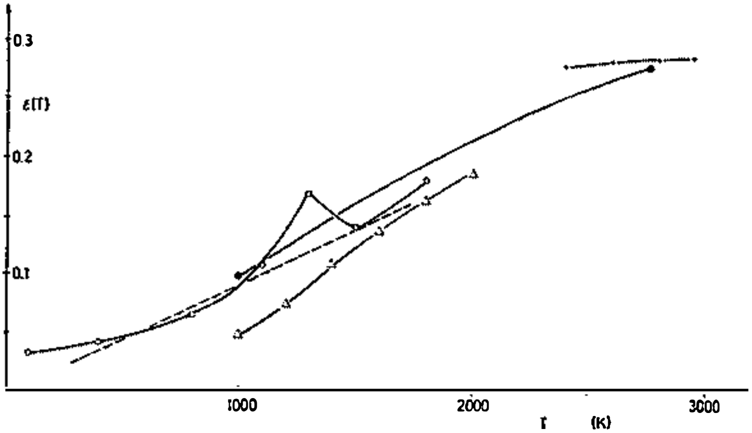

Fig. 1 Comparison of total emissivities from different references: ○ from Ref.[4], + from Ref.[5], △ from this work, ——— from the Hagen-Rubens equation (resistivity taken from Ref.[4]), and ● from Ref.[6].

In the log-log scale we found the following linear relation for the maximum-spectral-radiance wavelength:

$$\lambda_m \cdot T^{6/7} = 8.4 \cdot 10^2 \ (\mu\mathrm{m} \cdot \mathrm{K}^{6/7}) \quad \ldots \quad 1000\ \mathrm{K} < T < 2000\ \mathrm{K}.$$

This empirical expression departs from data in Table 2 by not more than $-1.9\ \%$ to $+1.2\ \%$.

The normalized curves are shown in Fig. 2. Agreement between the normalized curves for different temperatures is not so good as it was in the case of tungsten radiance1) and therefore a single generalized black-body equation was not sought. The integral of the normalized curves, evaluated with plausibly extrapolated curves, appeared to be also slightly temperature dependent, being larger for lower temperatures. For $T = 1000$ K, the integral is equal to 1.32, for $T = 1200$ K to 1.29, and for the other temperatures to 1.23. In the case of Planck's radiation the integral is equal to 1.49 while for tungsten it was 1.29.

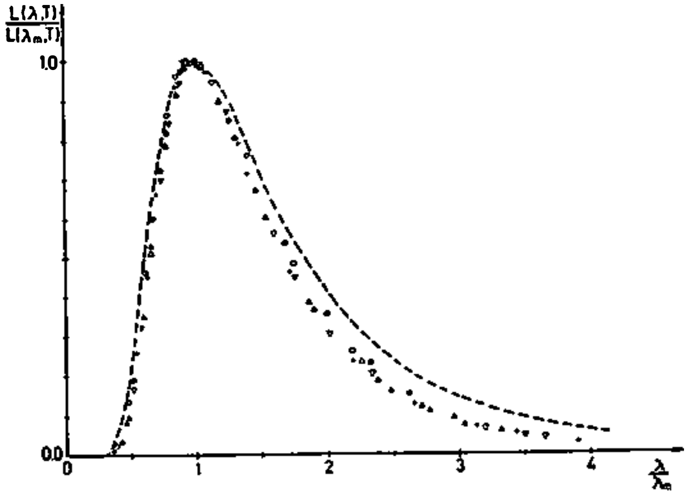

Fig. 2 Normalized curves for different temperatures. On the ordinate the reduced spectral radiance

$L(\lambda, T)/L(\lambda_m, T)$ is plotted, and on the abscisae the reduced wavelength λ/λ_m.

○ 1000 K, ● 1200 K, △ 1400 K, ▲ 1600 K,
▽ 1800 K, + 2000 K, ——— the normalized black-body curve.

Comparing the emissive properties of molybdenum with those of tungsten no linear relation between the total normal emissivity and temperature was found, the total radiance was not proportional to a particular power of temperature, and single normalized curve could not be drawn. A similar set of data describing emissive properties of other metals, should be very interesting.

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ANALIZA EMISIJSKIH SVOJSTAVA MOLIBDENA U INTERVALU TEMPERATURA OD 1000 DO 2000 K

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Sadržaj

Koristeći podatke o normalnoj emisiji usijane površine molibdena2), izrađena je tablica normalnog spektralnog energetskog sjaja (spektralne radijacije) u intervalu temperatura od 1000 do 2000 K i u intervalu valnih duljina od 0,4 do 5,0 μm. Time je omogućeno korišćenje usijane trake molibdena kao standarda zračenja.

Na osnovu krivulje spektralnog energetskog sjaja pokazano je kako se s temperaturom vlada integralno zračenje, totalna emisija, maksimalni spektralni sjaj i valna duljina tog maksimuma.

Utvrđeno je da se samo valna duljina maksimuma zračenja vlada linearno u log-log predočivanju, pa je za nju određena empirijska relacija. Totalna emisija uspoređena je s podacima iz literature u širem intervalu temperatura (sl. 1). Reducirane krivulje spektralnog sjaja (sl. 2) pokazuju izvjesno razilaženje i ne mogu se opisati zajedničkom formulom oblika poopćenog Planckovog zakona.