THERMAL RADIATION OF LIQUID METALS

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A unified generalized dependence for calculating hemispherical integral fluxes of thermal radiation of liquid metals has been obtained. The authors established a periodicity of the thermal radiation of liquid metals and its relation to a characteristic of the bonding strength − the Debye temperature.

Theoretical methods of calculating the radiation characteristics of liquid metals are practically not developed. In [1] it is stated that the emissivity of a metal does not change in melting. In other cases [2], to find them, use is made of methods developed for solids. The drawbacks inherent in these methods remain and, perhaps, even increase in the liquid phase. Experimental measurements have been performed for a small number of metals in a limited temperature range.

In this work, we generalize experimental data on the thermal radiation of liquid metals based on the functional dependence [3]

$$U = \varphi\,(S/R)\,, \quad U = q/q_1\,, \tag{1}$$

the derivation of which has no limitations on the type of phase, and it can be applied to melts. In expression (1) the scale flux q_1 for each liquid metal was taken equal to q for an adopted constant value of the entropy for all metals. The hemispherical integral emissivity factor for calculating q for a number of metals was found from the normal integral emissivities according to the procedure of [4].

The scale flux is proportional to the combination $(k\Theta)^4/c^2h^3$ [3]. The Debye temperature characterizes the bonding strength. Its application to melts according to [5] is even more preferable than to solids.

The functional dependence (1) holds true for each class of substances. In the case of structural changes (polymorphic transformations, postmelting effects), the scale fluxes must be determined anew. If continuous structural transformations occur in the liquid metal as the temperature increases, the scale flux as a quantity determined by the structure of the substance must also change with the temperature.

Results of the use of dependence (1) for generalization of experimental data [6-14] on integral hemispherical fluxes of thermal radiation of liquid metals are shown in Fig. 1. For convenience, part of the data is shifted down by half a unit (line *B*) and a unit (line *C*) of the vertical-axis scale. The scale fluxes are referred to the value $S/R = 10$ (Table 1). The entropy of the liquid metals was taken from reference books [15-17].

The averaging curve of the generalized dependence corresponds to the equation

$$\log U = 0.708 \left(\frac{S}{R}\right) - 0.005 \left(\frac{S}{R}\right)^2 - 6.58\,. \tag{2}$$

The deviation of the majority of the data from the averaging curve (2) does not exceed ±10%; for a number of elements (Si, Ge, Sb, Bi), the calculations by (2) at temperatures 100−200 K higher than the melting temperature are overstated. Furthermore, the scatter of the experimental points in the generalization for Ti, Fe, Co, and Ni turns out to be large. This is attributable to the instability of the structure of liquid metals.

The structure of many liquid metals in the vicinity of the melting temperature is similar to the structure of their crystals in the solid phase [5, 18, 19]. During the melting of semimetals and semiconductors partial breaking of covalent bonds occurs. The reorganization of their structure does not end at this. As the tempera-
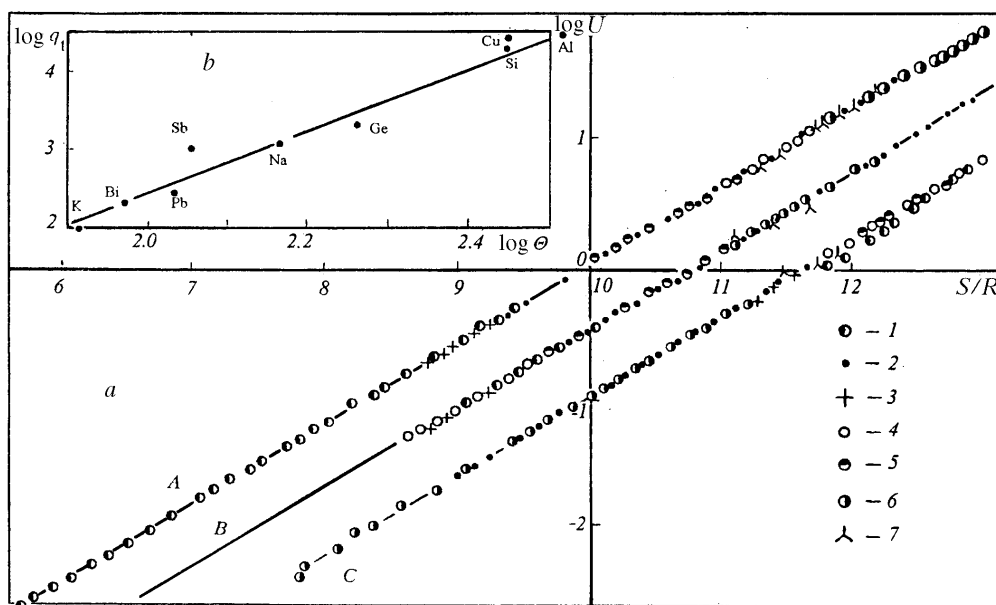
Fig. 1. Generalization of experimental data on the thermal radiation of pure liquid metals (a)

Lines	Elements						
	1	*2*	*3*	*4*	*5*	*6*	*7*
A	Li	K	Mg	Ca	Cu	Ti	Bi
B	Zn	Sn	Hg	Al	Cd	Pb	Ni
C	Sb	In	Si	Ge	Co	Na	Fe

and dependence of the scale fluxes on the Debye temperature (b).

ture increases further, the remaining covalent bonds break partially or fully, while the number of free electrons and the coordination number continue to grow [5, 18, 19]. As the temperature increases, a change in the melt structure can also be observed for metals that have phase transitions in the solid state. Liquid iron in the vicinity of the melting temperature corresponds to the structure of solid δFe, and when the temperature increases by 160–220 K − it corresponds to the structure of γFe [19]. Shvarev et al. [6] discovered a small inflection on the dependence of the normal integral emissivity of pure iron in the vicinity of 1920 K; they relate this inflection to a change in the atomic and electronic structure.

The complex character of the change in the structure of melts leads to postmelting effects − an anomaly of structure-sensitive properties (viscosity, velocity of ultrasound) [5]. There are not enough data on the structure of liquid metals with a changing structure. It has become possible to refine the scale fluxes for Sb, Bi, and Ge, for which there are detailed measurements of the velocity of ultrasound. The latter is proportional to the Debye temperature [5].

The dependence of the velocity of ultrasound on the temperature is linear for liquid metals up to the melting temperature. This linearity is disrupted in the presence of postmelting effects. For antimony, for example, as the temperature decreases, the velocity of ultrasound a passes through a maximum and then decreases sharply to the melting temperature (Fig. 2). Since the scale flux is proportional to the Debye temperature and hence the velocity of ultrasound to the fourth power, its change is allowed for using a correction factor γ that is equal to the ratio of the actual velocity of ultrasound to that linearly extrapolated to the postmelting interval from the high-temperature region to the fourth power. It is less than unity and as the temperature increases approaches it (Table 2).

The scale fluxes reveal a periodicity (Fig. 3) that is typical of a number of physicochemical properties of the elements. Regarding the nature of the curves and the alternation of the maxima one observes a satisfactory correlation with the analogous dependence of the Debye temperatures [5]. The fourth, fifth, and sixth pe-

TABLE 1. Scale Fluxes and Debye Temperatures of Liquid Metals

No.	No. of the element	Element	q_1, W/m^2	Θ, K according to [5]	Θ', K	Θ'', K	Θ, K by Eq. (3)
1	3	Lithium	101900	–	–	–	442
2	11	Sodium	1298	147	161	215	148.5
3	19	Potassium	104.7	82	101	125	79
4	12	Magnesium	26427	–	–	–	315
5	20	Calcium	3524	–	–	–	191
6	22	Titanium	20890	–	–	–	297
7	41	Niobium	10060	–	–	–	248
8	26	Iron	22680	–	–	–	304
9	27	Cobalt	24550	–	–	–	310
10	28	Nickel	30200	–	–	–	326
11	29	Copper	25700	280	273	296	313
12	30	Zinc	6986	–	233	267	226
13	48	Cadmium	1265	–	148	130	148
14	80	Mercury	187	–	105	85	91.5
15	13	Aluminum	27085	332	335	262	317
16	49	Indium	780	–	143	101	130
17	14	Silicon	22079	279	270	245	302
18	32	Germanium	2257	183	183	166	170.5
19	50	Tin	710	–	143	116	128
20	82	Lead	279	108	123	103	101
21	51	Antimony	1035	114	109	96	–
22	83	Bismuth	217	94	85	73	95
23	37	Rubidium	35[*]	–	–	–	60
24	55	Cesium	9.1[*]	40	39	46	43
25	47	Silver	5190[*]	192	196	203	210
26	79	Gold	1755[*]	–	150	143	160
27	31	Gallium	3126[*]	198	198	185	185
28	81	Thallium	312[*]	–	115	99	104
29	23	Vanadium	40050[*]	–	–	–	350
30	73	Tantalum	4000[*]	–	–	–	197

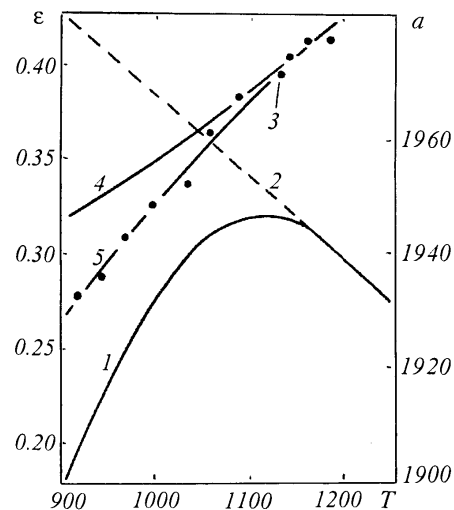[*] Estimate of the authors by Eq. (3) and Fig. 3.

Fig. 2. Velocity of ultrasound (1, 2) and hemispherical integral emissivity (3–5) of liquid antimony in the vicinity of the melting temperature: 1 and 3) experimental data of [5] and [12], respectively; 2) linear extrapolation to low temperatures; 4) calculation by Eq. (2) for a constant scale flux; 5) the same but for a corrected scale flux. a, m/sec; T, K.
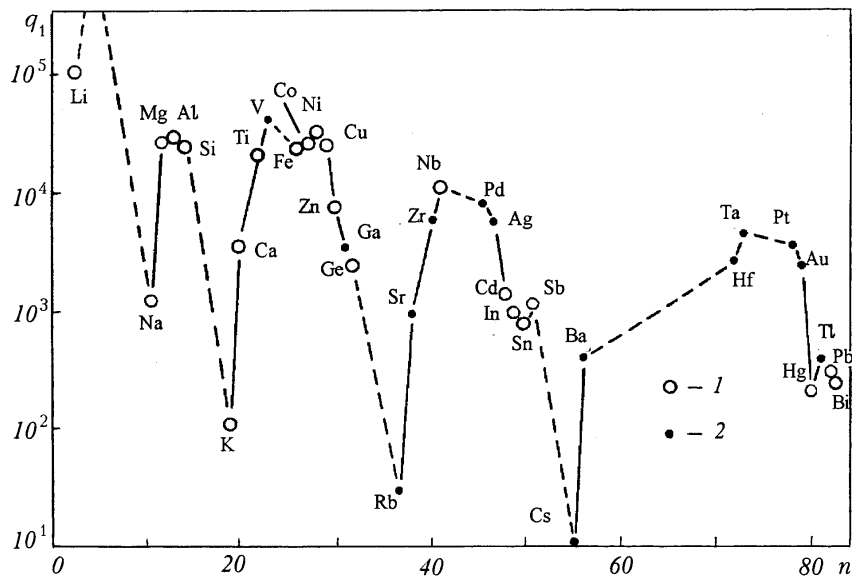
Fig. 3. Periodicity of the scale fluxes of liquid metals: 1) experimental data; 2) estimate of the authors. q_1, W/m^2.

TABLE 2. Coefficients γ of Antimony, Bismuth, and Germanium

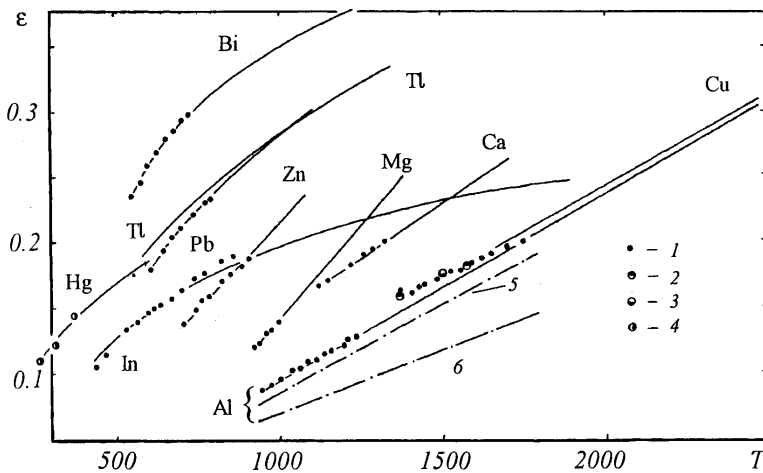| Element	$T-T_m$, K					
	0	50	100	150	200	250
Sb	0.83	0.89	0.93	0.96	0.98	1.0
Bi	0.967	0.977	0.991	1.0		
Ge	0.976	0.990	1.0			

Fig. 4. Hemispherical integral emissivities of liquid metals: 1) [12]; 2) [8]; 3) [13]; 4) [1, 14]; 5) [9]; 6) [10]; the solid lines denote calculation by Eq. (2).

riods of the periodic law have peaks whose shape is qualitatively the same. As the number of the period increases, the absolute values of q_1 decrease.

Depending on the Debye temperature, the scale fluxes for liquid metals are grouped in logarithmic coordinates near a straight line with an angular coefficient of 4 (see Fig. 1b):

$$\log q_1 = 4 \log \Theta - 5.574 . \qquad (3)$$

Debye temperatures for liquid metals calculated from the velocity of ultrasound are given in [5] (see Table 1). The work also shows a plot of Θ values found from the velocity of ultrasound and the viscosity of

1173

liquid metals. Values of Θ taken from a small-size plot are denoted in Table 1 by Θ' (for ultrasound) and Θ'' (for viscosity).

Equation (3) and Fig. 3 can be used for preliminary evaluation of scale fluxes by means of the Debye temperature or by means of the neighbors in the periodic law. The scale fluxes found in this way make it possible to predict the emissivities for uninvestigated liquid metals. As an example Fig. 4 gives the emissivity for thallium.

Equation (2) can be used to find the emissivities of metals at high temperatures up to the values $S/R = 13.5$. The calculated and experimental emissivities (Fig. 4) agree within the limits of their measurement error. The results of three works [9, 10, 12] for liquid aluminum differ significantly. The data of [10] (line 6 in Fig. 4) are practically an extension of the dependence of the emissivity on the temperature for solid aluminum and are 25–30% lower than the results of [12]. The data from another work of the same authors [9] are higher (line 5 in Fig. 4) and differ by 7–9% from [12]. Therefore the results of [9, 12] should be recognized as reliable.

In conclusion we note that if the scale fluxes are established for liquid metals from thermal radiation or by some other method, they are used to determine (see Eq. (3)) unknown Debye temperatures (Θ in the last column of Table 1).

NOTATION

q and q_1, hemispherical integral density of the thermal-radiation flux and its value at $S/R = 10$; $U = q/q_1$, relative flux; k and h, Boltzmann and Planck constants; c, velocity of light; Θ, Debye temperature for the liquid metal; S, entropy; R, gas constant; γ, ratio of the actual velocity of ultrasound to that linearly extrapolated to the postmelting interval from the high-temperature region to the fourth power; ε, hemispherical integral emissivity; n, number of the element in the periodic law of D. I. Mendeleev.

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