DETERMINATION OF THE CONSTANTS OF VAPORIZATION OF METAL PARTICLES IN AN ARC PLASMA

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We made measurements of the constants of vaporization of spherical metal particles in an arc plasma. The data of the experiments were compared with approximate calculations. It was shown that the time required for complete vaporization of the particles was 30-40% more than the time found by using the vaporization constants, owing to a nonstationary stage and to deviation from V. Streznevskii's law.

The vaporization of small particles is a fairly complex process, and a number of simplifications [1-3] are generally introduced in describing it. If a particle is spherical in shape and its radius is much larger than the mean free path of the vapor molecules ($r \gg 1$) then the rate of vaporization when the surface of the particle has reached a stationary temperature is described by the formula [2]

$$\frac{dm}{dt} = -\frac{2\pi \lambda_m (T_\infty - T_{st}) r}{L} \Phi \mathrm{Nu}, \tag{1}$$

where

$$\Phi = \ln\left[1 + \frac{c_p (T_\infty - T_{st})}{L}\right] \frac{L}{c_p (T_\infty - T_{st})}$$

is a parameter which takes account of the effect of the displacement of the resulting vapors on the heat exchange with the surface of the drop. Integration of (1) yields a relation first established experimentally by V. Sreznevskii [4]:

$$r^2 = r_0^2 - Ct. \tag{2}$$

The vaporization constant C characterizes the rate at which the surface of the drop decreases with time for the given conditions:

$$C = \frac{d(r)^2}{dt} = \frac{\lambda_m (T_\infty - T_{st})}{L\rho} \Phi \mathrm{Nu}. \tag{3}$$

In the use of an arc discharge in plasmochemical technology, metallurgy, metal processing, and emission-spectrum analysis, it is a matter of considerable interest to estimate the rate of vaporization of the particles in the arc plasma.

Since the heat flux caused by radiant heat transfer in the arc plasma constitutes a very small fraction of the total heat balance [5, 6], it is usually neglected. As is shown by the calculation of [7], the Reynolds numbers for the motion of small particles in plasma are small, and the conditions of flow past the particles may be regarded as Stokesian. In this case heat transfer from the particle takes place chiefly through thermal conductivity [8]. For this reason, in making calculations we may start with the relations (1)-(3) and use the quantity C to characterize the quasistationary vaporization of a particle in the plasma, setting $\mathrm{Nu} = 2$.

We studied the vaporization of spherical metal particles having radii of $4\text{-}20 \cdot 10^{-5}$ m, freely falling in the arc plasma or brought into the central part of the discharge on a thin carbon rod. We used a constant-current arc burning between carbon electrodes (the current value was 15 A).

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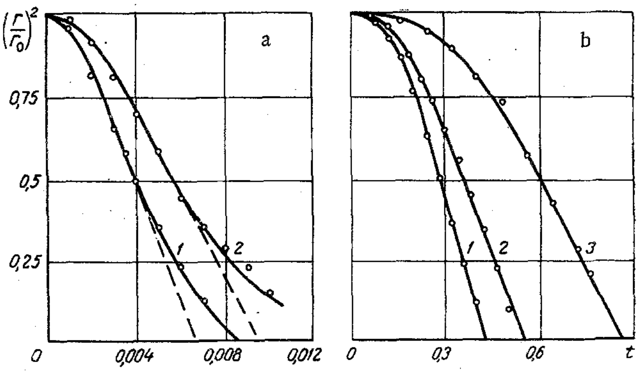

Fig. 1. Variation of the ratio $(r/r_0)^2$ as a function of time t, sec: a) vaporization of particles falling in plasma [1) Pb, $r_0 = 4.8 \cdot 10^{-5}$ m; 2) Pb, $r_0 = 6.1 \cdot 10^{-5}$ m]; b) from carbon-rod channel [1) Bi, $r_0 = 11 \cdot 10^{-5}$ m; 2) Pb, $r_0 = 11.5 \cdot 10^{-5}$ m; 3) Sn, $r_0 = 10 \cdot 10^{-5}$ m].

TABLE 1. Determination of the Constant C and the Vaporization Time for Lead Particles Falling in Plasma

$r_0 \cdot 10^5$, m	$C \cdot 10^8$, m^2/sec	t_{st}, sec	t_c, sec
4,8	41,8	0,0056	0,0085
6,1	47,8	0,0079	0,0125
6,3	38,6	0,0103	0,014
7,3	48,4	0,011	0,0155

To measure the constants of vaporization of the metal particles in the plasma, we used a spectroscopic method and absorption radiography [9]. Both methods enabled us to determine the mass of a particle, or its radius, during the vaporization process, and to obtain curves showing the variation of the square of the radius as a function of time (Fig. 1). In the graphs of $(r/r_0)^2 = f(t)$ we can distinguish three sections corresponding to separate stages of the vaporization: a nonstationary stage, vaporization at stationary particle-surface temperature in accordance with (2), and deviation from this relation when the radius of the particle becomes comparable with x. The constant of vaporization was determined from the tangent of the angle of inclination of the linear section of the $(r/r_0)^2 = f(t)$ curve:

$$C = r_0^2 \operatorname{tg} \alpha = A r_0^2 . \tag{4}$$

Table 1 shows the results of the measurements of the vaporization constant for lead particles of various sizes becoming vaporized as they move in the plasma of an arc discharge. The dispersion of the values of the constant C was characterized by a coefficient of variation equal to 10.8%. For lead particles introduced into the plasma at the end of a carbon rod, we found v = 8.7% for particle radii varying from 8 to 14 $\cdot 10^{-5}$ m.

The average values of the vaporization constants, obtained by averaging 3-12 measurements made for identical conditions of particle vaporization, are shown in Table 2. It can be seen from these data that the value of C depends on the temperature of the medium and varies with the thermophysical properties of the metal being vaporized. For comparison purposes, Table 2 also shows experimental data for drops of water evaporating at atmospheric pressure in a stream of hot air (velocity 0.5 m/sec) [10], and also data obtained from the combustion of drops of hydrocarbons [11].

Our measured values for the vaporization constants were compared with the data of calculations performed according to formula (3). The calculation of the vaporization constants entails a certain amount of difficulty, since information on the thermophysical properties of substances at high temperatures is limited.

Using an arc burning between carbon electrodes, we assumed that the temperature of the plasma was 6250°K [12]. For a given temperature of the medium, the stationary temperature of the surface of the vaporizing particle can be found graphically by solving the equation obtained by Williams [3]. The T_{st} values calculated for the conditions of our experiments are shown in Table 2.

We found the coefficient of thermal conductivity of the plasma from the appropriate graphs showing its variation with temperature [13], assuming, in accordance with [14], a logarithmic-mean value between the temperature of the medium and the stationary temperature of the surface. We took λ_m for the mixture of air and the vapors of the substance being vaporized to be equal to the coefficient of thermal conductivity of air [15].

TABLE 2. Vaporization Constant for Particles of Various Compositions

Conditions of vaporization	Substance investigated	Vaporization constant, $C \cdot 10^8$, m^2/sec		T_{st}, °K, calculated data
		experimental data*	calculated	
Falling in plasma	lead	44±7.6	46.9	1840
	tin	26±4.4	27.6	2190
T_∞ = 6250 °K	silver	21±4	16.2	2200
From carbon-rod channel	bismuth	4.1±0.45	4.4	1550
	lead	3.6±0.28	3.6	1630
	tin	1.89±0.17	2.04	1950
T_∞ = 2700 °K	silver	1.58±0.16	1.3	1950
In air stream [10] T_∞ = 973 °K	water	4.76	–	–
Combustion [11] T_∞ = 2000 °K	benzene	24.2	–	–

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*The confidence limits were determined on the basis of a confidence probability of 0.95.

The values of L and c_p for the metals investigated were taken from [16].

The results of the calculations are shown in Table 2. They are in satisfactory agreement with the experimental data ($v = 13.2\%$). Thus, we may conclude that formula (3) enables us to estimate the constant of vaporization of metal particles in an arc plasma.

During the quasistationary vaporization of a particle in accordance with (2), its vaporization time is

$$t_{st} = \frac{r_0^2}{C}. \tag{5}$$

From the functions $(r/r_0)^2 = f(t)$ that we found (Fig. 1) it follows that the time required for complete vaporization of a particle is 30-40% more than t_{st} (Table 1) because the process includes a nonstationary stage and because, as a result of the small size of the particles, the rate at which the surface of a drop decreases deviates from a constant rate. Thus, in estimating the total vaporization time, the duration of these stages must also be taken into account.

NOTATION

m	is the mass of particle;
t	is the time;
t_c	is the time required for complete vaporization;
r	is the radius of particle;
r_0	is the initial value of r;
λ_m	is the coefficient of thermal conductivity of the mixture of air and the vapors of the substance being vaporized;
T_∞	is the temperature of medium;
T_{st}	is the stationary temperature of the surface of the drop;
L	is the latent heat of vaporization;
c_p	is the heat capacity of the vapor at constant pressure;
Nu	is the Nusselt number;
ρ	is the density;
C	is the vaporization constant;
x	is the free path length of vapor molecules;
v	is the coefficient of variation.

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