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BRIEF COMMUNICATIONS

Characteristics of the Heating Dynamics of a Graphite Conductor Taking into Account the Skin Effect

P. V. Novikov* and G. N. Churilov**

** Krasnoyarsk State Technical University, Krasnoyarsk, 660074 Russia*

*** Kirensky Institute of Physics, Siberian Division, Russian Academy of Sciences, Akademgorodok, Krasnoyarsk, 660036 Russia*

E-mail: churilov@iph.krasn.ru

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Abstract—Calculations for a one-dimensional model of RF heating of a cylindrical graphite conductor have been carried out. The heating dynamics are analyzed in the general form. Conductor temperature profiles and the times for heating up to the graphite sublimation temperature as a function of current and frequency have been obtained. A model of conductor heating with partial return of the energy irradiated by the conductor surface has been considered. Frequency and current ranges have been determined to carry out this graphite sublimation method in a chamber with reflecting walls. The problem is associated with carbon vapor production and subsequent synthesis of fullerenes and other carbon structures. © *2000 MAIK "Nauka/Interperiodica"*.

INTRODUCTION

Metals in the form of finely dispersed powders find an ever expanding use in technology. Heating conductors in the form of wires by passing high pulsed currents [1] is one of the effective ways of obtaining these materials. In 1990, arc sputtering of carbon was employed by a group of German physicists, which led them to the discovery of a method for fullerene synthesis [2]. The method consisted in the sputtering of carbon by a direct or alternating current arc in a helium atmosphere at a pressure of 100 torr. Afterwards, many other fullerene synthesis methods were developed. But in spite of the great diversity of these methods, their productivity did not exceed several grams per hour [3–9]. The common feature of all these methods is that carbon is first transformed into a plasma at a temperature of 6000–7000 K and then, during subsequent cooling (usually in a helium gas atmosphere), fullerene molecules are formed. The sublimation temperature of graphite in vacuum is about 4000 K. Unfortunately, the carbon plasma temperature at which fullerene molecules can be formed is unknown. We assume that this temperature is below 6000 K and that fullerenes can be synthesized from carbon vapor produced by graphite sublimation. The heating necessary for graphite sublimation can be effected by passing a current through a graphite rod.

It is evident that, when a direct current is passed through a graphite rod, the temperature near its axis exceeds that at the surface due to radiation losses. Sublimation will start first in cracks and voids in the graphite before expanding to other regions, which will lead to mechanical destruction of the graphite rod. Therefore, RF heating should be used, because due to the skin effect the joule heat will then be released mostly in the conductor surface layer [10].

In this paper, we consider the dynamics of heating a cylindrical conductor by RF currents to the temperature at which sublimation starts.

THE MODEL

Heating a conductor in vacuum is described by a nonstationary equation for heat conductivity in cylindrical coordinates [11]

$$c\rho\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(\lambda r\frac{\partial T}{\partial r}\right) + q_V(r), \qquad (1)$$

where $c = c_V$ is the specific heat, ρ is the density, λ is the heat conductivity, and $q_V(r)$ is the power of the volume heat sources.

Let us denote the boundary conditions at the conductor axis as

$$-\lambda\frac{\partial T}{\partial r}\bigg|_{r=0} = 0 \qquad (2)$$

and at the conductor surface as

$$-\lambda\frac{\partial T}{\partial r}\bigg|_{r=r_0} = -q_r(T)\big|_{r=r_0}, \qquad (3)$$

where $q_r(T) = \varepsilon\sigma_c T^4$ is the radiation flux density from the conductor surface; σ_c is the Stefan–Boltzmann constant; ε is the integrated emittance; and the initial condition is $T(r, t = 0) = T_0$ where $T_0 = 293$ K.

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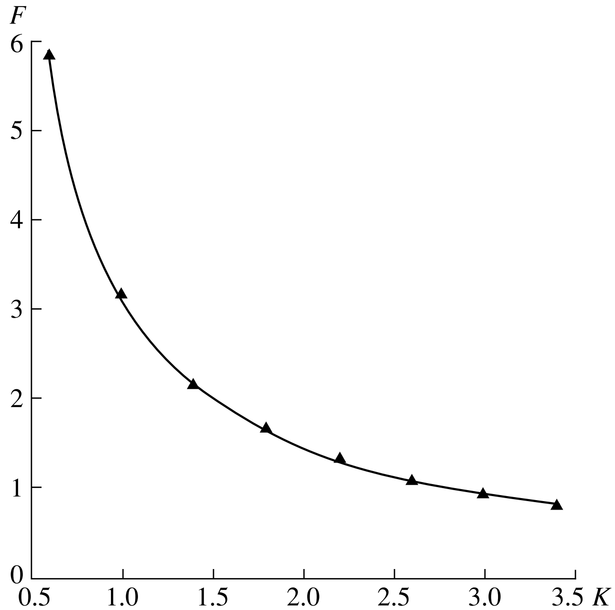

Fig. 1. Time for reaching the sublimation temperature F as a function of the dimensionless parameter K ($r_0 = 5 \times 10^{-2}$ m, $\Delta = 0.14$, $\alpha = 0$, and F is time in arb. units).

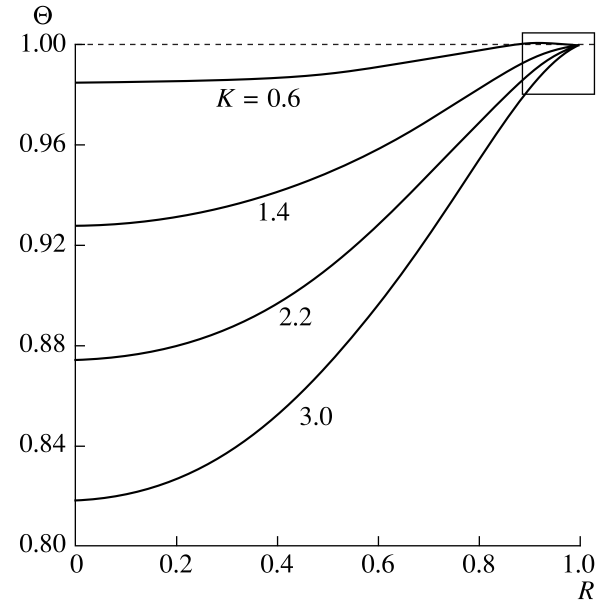

Fig. 2. Temperature profiles at the start of sublimation for different values of the parameter K ($r_0 = 5 \times 10^{-2}$ m, $\Delta = 0.14$, $\alpha = 0$). The portion in the rectangle is shown scaled up in Fig. 3.

In equation (1), the joule power of volume sources is determined as follows [10]:

$$q_V(r) = \frac{\overline{j^2}(r)}{\sigma} = \frac{Q}{\pi r \delta}\exp(-2(r_0 - r)/\delta), \quad (4)$$

where $\delta = \sqrt{2/(\mu\sigma\omega)}$ is the skin layer thickness, $Q = I^2/(2\pi\sigma\delta r_0)$ is the thermal power per unit length of the conductor, r_0 is the conductor radius, σ is the electrical conductivity, $\mu \approx \mu_0$ is the magnetic permeability, I is the effective current, and ω is the current frequency.

Let us introduce normalized variables of the transfer process

$$R = \frac{r}{r_0}, \quad F = \frac{at}{r_0^2}, \quad \Theta = \frac{T}{T_e}, \quad \Delta = \frac{\delta}{r_0},$$
$$K = \frac{Q}{\lambda T_e}, \quad \xi(\Theta) = \frac{r_0}{\lambda T_e} q_r(T), \quad (5)$$

where R and F are the spatial and time coordinates ($a = \lambda/c\rho$ is the thermal diffusivity); Θ is the relative temperature; Δ is the relative skin layer thickness; and K and ξ are parameters characterizing the specific power Q and the density q_r of the radiation flux from the surface, respectively.

In this way, the number of initial parameters can be reduced, and a solution in a general form can be obtained. With the new variables, the system (1)–(3) can be written as

$$\frac{\partial \Theta}{\partial F} = \frac{1}{R}\frac{\partial}{\partial R}\left(R\frac{\partial \Theta}{\partial R}\right) + \frac{K}{\pi R \Delta}\exp(-2(1 - R)/\Delta), \quad (6)$$

$$\left.\frac{\partial \Theta}{\partial R}\right|_{R=0} = 0, \quad \left.\frac{\partial \Theta}{\partial R}\right|_{R=1} = -\xi(\Theta)|_{R=1}. \quad (7)$$

The solution contains two parameters, K and Δ. The current, frequency, and time can be expressed through the generalized parameters as follows:

$$I = r_0\sqrt{2\pi\sigma\Delta K \lambda T_e},$$
$$\omega = \frac{2}{(r_0\Delta)^2\mu\sigma}, \quad (8)$$
$$t = \frac{F r_0^2}{a}.$$

CALCULATION RESULTS

Computer calculations were performed by the finite-difference method. The iteration algorithm provided second-order accuracy of the spatial and time steps [11]. Profiles of the conductor temperature at the moment when sublimation started on its surface and the time elapsed until this moment were calculated for different values of K and Δ. As the parameter K and, correspondingly, the power Q is increased, the time of heating to the sublimation temperature T_e decreases (Fig. 1). The radial temperature gradient rises (Fig. 2). Under these conditions, overheating of the conductor's central region does not occur when the sublimation temperature is reached on the surface.

Due to radiation losses, the temperature maximum occurs not at the conductor surface but close to it

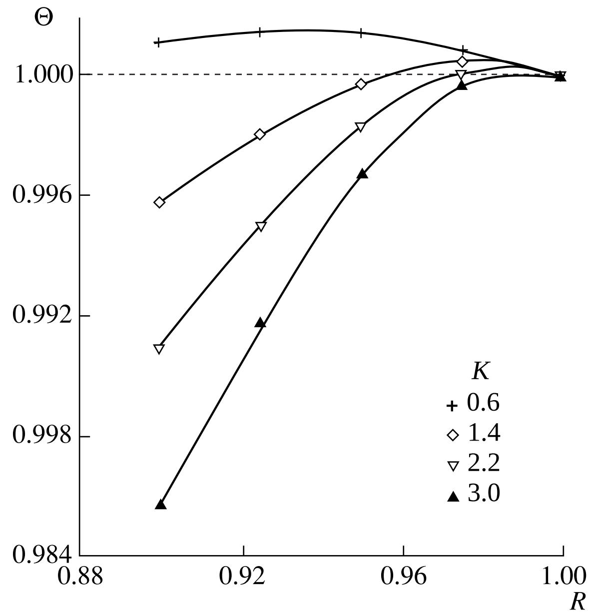

Fig. 3. Temperature profiles near the surface at the start of sublimation for different values of the parameter K ($r_0 = 5 \times 10^{-2}$ m, $\Delta = 0.14$, $\alpha = 0$).

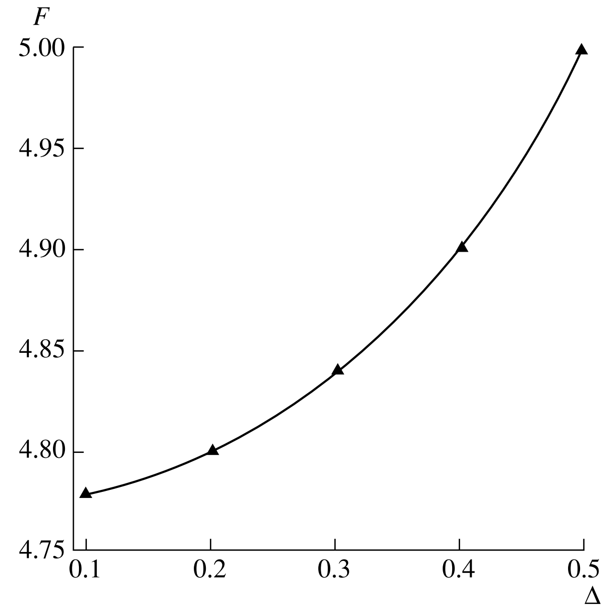

Fig. 4. Time taken to reach the sublimation temperature F as a function of the dimensionless parameter Δ ($K = 0.7$, $r_0 = 5 \times 10^{-2}$ m, $\alpha = 0$, and F is time in arb. units).

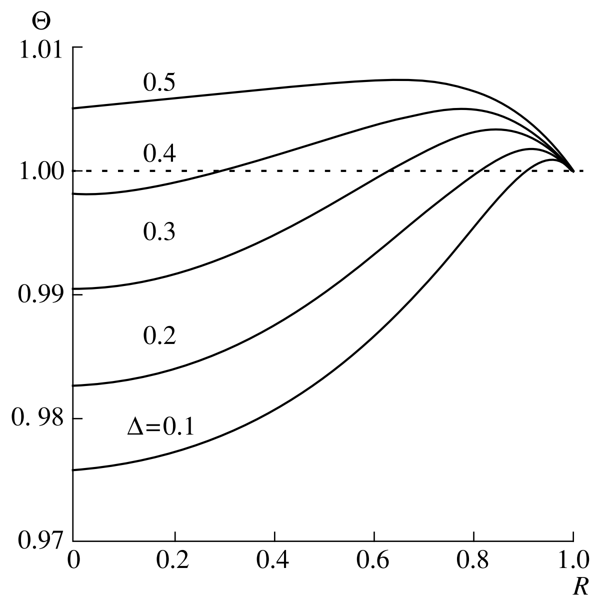

Fig. 5. Temperature profiles at the start of sublimation for different values of the parameter Δ ($K = 0.7$, $r_0 = 5 \times 10^{-2}$ m, $\alpha = 0$).

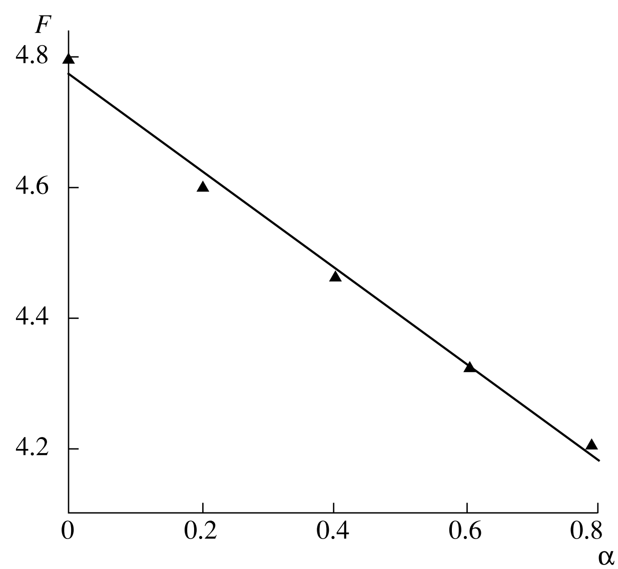

Fig. 6. Time taken for reaching the sublimation temperature F as a function of the coefficient α ($K = 0.7$, $\Delta = 0.14$, $r_0 = 5 \times 10^{-2}$ m, and F is time in arb. units).

(Fig. 3). As the parameter K increases, the maximum shifts towards the surface because of increasing heat release.

To evaluate the experimental potentialities of graphite sublimation as a means of synthesizing new carbon structures, we used the following values of the thermophysical parameters [12] for carbon, which were assumed to be constant during heating: specific heat c = 2.1 J/(g K), density ρ = 2.1 g/cm^3, heat conductivity λ = 2.66 W/(cm K), integrated emittance ε = 0.56, electrical conductivity $\sigma = 1.13 \times 10^4$ S/cm^2, and sublimation temperature T_e = 4473 K. For a graphite conductor of radius 5×10^{-2} m, the parameter range K = 0.4–3.4, according to (8), corresponds to a current range of 3.5–10.0 kA, and the time necessary to reach sublimation is 3.0–0.5 s (Fig. 1). If the current is reduced, by the time the sublimation temperature is reached at the surface, the conductor will be heated almost uniformly through-

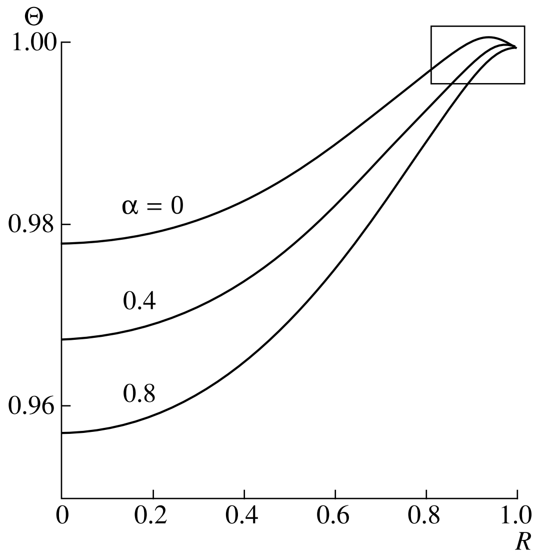

Fig. 7. Temperature profiles at the start of sublimation for different values of the parameter α ($K = 0.7$, $\Delta = 0.14$, $r_0 = 5 \times 10^{-2}$ m). The portion in the rectangle is shown scaled up in Fig. 8.

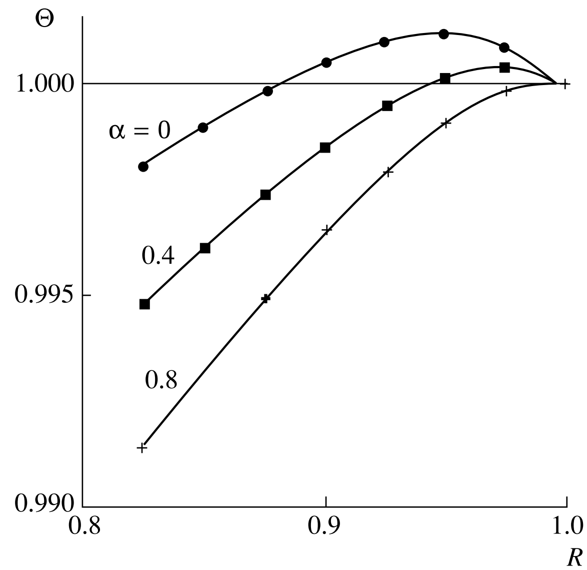

Fig. 8. Temperature profiles near the surface at the start of sublimation for different values of the parameter α ($K = 0.7$, $\Delta = 0.14$, $r_0 = 5 \times 10^{-2}$ m).

out its volume. If the current is increased, the heating time becomes too short and the process approaches the pulse heating described in [1, 13].

With increasing parameter Δ (which corresponds to decreasing frequency ω), the rod heating time increases, since both the volume heat release (see equation (6)) and the radial temperature gradient (Fig. 5) decrease due to the fact that with decreasing frequency the skin layer spreads over the conductor volume.

For a graphite conductor of radius 5×10^{-2} m, the range of 0.1–0.5 of the parameter Δ corresponds to the frequency range of 900–35 kHz. The calculations show that even when skin layer thickness is 0.4–0.5 of the conductor radius the inner conductor regions are considerably overheated (Fig. 5). Thus, a further decrease in the current frequency will result in an increase in the skin layer thickness that will make the use of RF heating unwarranted.

The calculations and estimations presented have shown that to produce the high currents corresponding to sublimation is, in practice, a very complicated task. Therefore, we changed the model of heating and calculated temperature profiles for a system with the following boundary condition at the surface:

$$-\lambda \frac{\partial T}{\partial r}\bigg|_{r = r_0} = -(1-\alpha) q_r(T)\big|_{r = r_0}. \qquad (9)$$

Experimentally, this boundary condition can be created, for example, using a cylindrical heating chamber in which the walls have reflectance α.

The higher the reflectance of the walls, the shorter the time of heating to the sublimation temperature T_e (Fig. 6) and the higher the radial temperature gradient (Fig. 7). Moreover, at higher values of the reflectance α, the temperature maximum approaches the surface (Fig. 8); and at α = 0.6–0.8, it is found at the conductor surface.

The partial heat recovery also reduces power consumption. Thus, for a conductor of radius 5×10^{-2} m at α = 0.8, the reasonable range of the parameter K is 0.15–2.2, corresponding to a current of 2.0–8.0 kA and a time necessary to reach sublimation of 8.0–0.5 s.

CONCLUSIONS

(1) The dynamics of conductor RF heating has been analyzed in the general form as a function of the generalized parameters.

(2) Conductor temperature profiles and the times of heating to the sublimation temperature for currents of 2–10 kA in the frequency range of 35–900 kHz have been calculated using parameters corresponding to artificial graphite.

(3) Specific ranges of the control parameters have been determined to carry out graphite sublimation with reflecting walls at α = 0.8.

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