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Letters to the Editor

Temperature measurement of carbon arc plasma in helium

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Experimental investigations on the process of fullerene synthesis in carbon arc plasma reactors were related to measurements of fullerene yield dependence on the type of inert gas and gas pressure, current intensity and interelectrode space [1,2]. The effect of gas flow on the efficiency of the process of fullerene synthesis have been investigated [3]. Spectroscopic investigations of a carbon arc in atmospheres of different inert gases are presented in Ref. [4]. These results can be summarized as follows: (a) the efficiency of fullerene synthesis decreases with decreasing thermal conductivity of an inert gas. The maximum fullerene yield is in helium and the minimum is in xenon. The fullerene yield depends slightly on gas pressure. (b) The fullerene yield has a maximum value at 100 A current intensity if the interelectrode spacing is about 4 mm. (c) The fullerene yield has a maximum value under the defined value of gas flow rate. (d) It was found that the mean plasma temperature of a carbon arc in helium atmosphere was in the range $5–7\times10^3$ K [5].

The process of carbon cluster formation took place in an inert heat bath whose geometry was determined by the temperature gradient between the arc axis and chamber walls. The ratio of values of carbon vapour concentration and velocity of carbon jet from the inert heat bath determine the efficiency of collisions among carbon clusters.

As a result of anode erosion in the hot jet that expands from the interelectrode space, a certain number of carbon atoms and ions are produced. The process of clustering of carbon atoms into small chains starts in the interelectrode space. Higher clusters (rings, caged structures) are formed in the funnel shaped jet of the hot gas. Plasma chemical reactions among carbon clusters can be described using the Smoluchovski equations [6]. After simple transformation they can be presented in the following form:

$$\frac{\mathrm{d}c_k}{\mathrm{d}X}=\sum_{j=1}^{k_m}\sqrt{1-\frac{X}{C}}\tilde{K}_{k-j,j}c_{k-j}c_j-\sum_{j=1}^{99}\sqrt{1-\frac{X}{C}}\tilde{K}_{kj}c_kc_j \qquad (1)$$

where dimensionless variable $X=\mathrm{Ar}$, parameter $C=\mathrm{AB}$, temperature parameter B and normalized reaction constant are:

$$\tilde{K}_{ij}=\sqrt{\frac{i+j}{i-j}}\frac{\sigma_{ij}}{\sigma_{11}},\quad A=\frac{N_c\sigma_{11}}{v}\sqrt{\frac{8k}{\pi M_c}}T_0\langle P_{ij}\rangle \quad \text{and}$$

$$B=RT_0/(T_0-T_w). \qquad (2)$$

The most important quantities that determine the efficiency of fullerene synthesis are N_c is the concentration of carbon in the interelectrode space; v is the velocity of carbon/helium fluid from the interelectrode space; T_0 is the arc axis temperature; T_w is the wall temperature; and R is the radius of the plasma reactor.

In this experimental work, the anode erosion rate, mean gas temperature and fullerene yield were measured. The primary goal of the experimental work was to verify the results of the theoretical analysis.

For the control of jet velocity we used the method of fullerene synthesis using a hollow cathode. By controlling the gas flow rate through the hollow cathode, we controlled the gas flow rate from the interelectrode space itself. Values of the anode erosion rate, mean plasma temperature and gas flow were combined in one parameter, which was proportional to variable X.

The mean current intensity ($I=100$ A) and high gas pressure ($p=700$ mbar) were chosen in order to achieve local thermodynamic equilibrium. In this case the measured vibrational temperature is equal to the real gas temperature.

Details of the experimental set-up were published previously [7]. The analysis of the light emitted from the

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carbon arc plasma was done using an ISP-51 medium resolution spectroscope with glass prisms. The range of wavelengths, which could be examined, was from 380 to 660 nm. The distance between arc and monochromator slit was 120 cm. The plasma was projected by lens onto the calibrated screen with a slit through which passed the light from the plasma. This light was projected onto the first prism by another lens located just in front of the slit. The spectra of the carbon arc in helium were registered by a CMOS digital camera. The spectra of Swan molecular band of cluster C_2 $\Delta v = 1$, were recorded with resolution of 0.11 nm/pixel and with spectral width of 0.1–0.2 nm.

The mean gas temperature dependence of electrode diameter under the experimental conditions [7] is presented in Fig. 1.

The fullerene yield dependence of the ratio of product of evaporation rate, mean temperature square root and gas flow squared value is presented in Fig. 2. This ratio is proportional to the dimensionless variable X.

The experimental results have shown that mean plasma temperature increases with decreasing electrode diameter. This result is explained by using the energy conservation law. The power, which has been developed under the arc discharge, is constant and equal to the product of current intensity and voltage. In this experiment, the power is about 2000 W. A fraction of this power (P_{PL}) is transferred to carbon atoms and clusters in the plasma, some (P_E) is dissipated in anode erosion and the remainder (P_C) is conducted through the anode to the cold end.

The power which was conducted through the carbon rod is proportional to the electrode diameter. We can conclude that the power which was invested in plasma heating and anode evaporation increases with decreasing electrode diameter by a square law. The energy of electrons dissipated on plasma heating is converted to radiation and

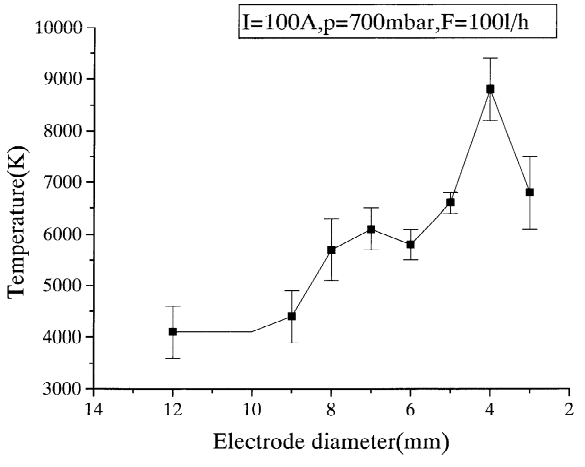

Fig. 1. The dependence of mean gas temperature on electrode diameter for current intensity of 100 A, gas pressure of 700 mbar He, gas flow 100 l/h, magnetic field B = 100 G.

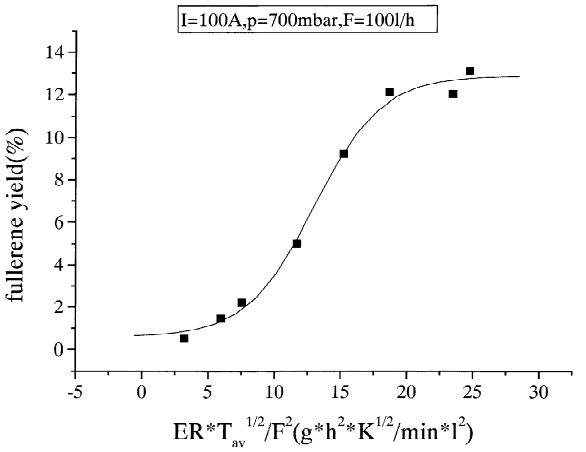

Fig. 2. The dependence of fullerene yield on the ratio of product of anode erosion rate, mean temperature square root and gas flow squared value at 100 A current intensity.

convection of hot gas from the interelectrode space. Based on measured C_2 molecule radiation, which exists only in the interelectrode space, we calculated the mean plasma temperature [8].

This increase of mean plasma temperature influences the dimensions of the inert heat bath in which plasma chemical reactions took place.

The dependence of fullerene yield on variable, which is proportional to X, is presented in Fig. 2. This dependence obtained experimentally is almost identical to the theoretical dependence of fullerene yield on variable X [6]. The highest transformation of carbon vapour into fullerene is obtained for electrodes with diameters of 5, 4 and 3 mm. This means that by further decreasing the electrode diameter, the fullerene yield is not increased. The maximum value of fullerene yield was 13.1%.

Our experimental results have shown that the fullerene yield was the highest when the product of carbon vapour concentration and the squared root of mean plasma temperature was the highest. Comparative analysis of experimental and theoretical results provides a better understanding of the fullerene formation mechanism.

Based on the results obtained, we can propose the following model of plasma reactor for producing high quantities of fullerenes. The proposed reactor must hold plasma with large dimensions (a small temperature gradient) and must have the possibility for independent control of carbon concentration and plasma velocity. Since the plasma temperature depends on carbon concentration (it decreases as carbon concentration increases) and velocity of plasma (increases as the velocity increases), it is necessary to find experimentally the situation at which the value of variable X the highest. The fullerene yield is the highest when the carbon concentration is great and velocity of plasma jet is low.

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Vapor-induced variation in electrical performance of carbon black/poly(methyl methacrylate) composites prepared by polymerization filling

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Recently, gas sensors or chemically sensitive resistors fabricated from conductive carbon black/polymer composites have received significant attention for use in detecting, quantifying and discriminating among various organic vapors [1–4]. The electrical resistance of these composites exhibits a drastic increase when the materials are exposed to some solvent vapors. The mechanism involved has been described on the basis of percolation theory. Upon exposure to an odorant, the composites will swell to varying degrees depending on the polymer–odorant interactions, and this swelling results in redistribution of the conductive fillers in the matrix and hence a change in the resistivity of the composites. It is found that the effect of swelling on the composite conducting capacity depends on the solvent nature [5]. Namely, there is at least one polymer capable of absorbing organic solvent vapors by dissolution or swelling process.

Tsubokawa et al. [6,7] reported that crystalline polymer-grafted carbon black/polymer composites show a great electric resistance response toward certain organic vapors. In their studies, crystalline polymers are grafted onto carbon black by direct condensation of the terminal groups of these polymers with hydroxyl groups or carboxyl groups on the carbon black surface using *N*,*N*′-dicyclohexylcarbodiimide (DCC) as condensing agent. Such a modification of carbon black can make its dispersion in polymer matrices more uniform and stable. Narkis and co-workers measured vapor response of carbon black-filled immiscible polyblends, like polypropylene/nylon 6 [4], high impact polystyrene/linear low density polyethylene [8]. Their

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