# HIGH-POWER PULSE GENERATORS OF LOW-TEMPERATURE PLASMA

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*The results of studies on high-power pulse generators of dense high-temperature plasma are analyzed. The main designs of sources based on a pulse plasmotron are examined. A design developed at a branch of the All-Union Scientific-Research Institute of Electrical Engineering has made it possible to obtain record helium-plasma parameters* ($T = 10^3-10^6$ K, $P = 10^9$ Pa)*. Areas of practical application of the sources are indicated.*

Pulse plasmotrons are the most efficient pulse source of dense high-temperature plasma [1]. The maximum parameters in regard to power input and pressure and temperature were obtained in these devices.

Various types of designs exist for pulse plasmotron chambers [1-4]. A feature common to all these designs is a cavity, most often insulated from the interior, into which electrodes are introduced. One wall of the cavity has a diaphragm, which opens when a certain pressure is reached. Discharge is initiated by a wire or a self-sustained arc mode. The latter method makes it possible to use power supplies with a lower voltage. The variation of the arc parameters with time, however, may cause the discharge to re-ignite as the pressure drops in the plasmotron chamber after part of the gas escapes from it.

Table 1 shows some of the main parameters of pulse plasmotrons made in the USSR and abroad [1-6].

In one possible pulse-plasmotron design, i.e., pulse-flow plasmotrons, gas flows through the plasmotron during combustion.

The latest developments and studies of pulse plasmotrons [3, 4] have substantially increased their parameters, especially in work with helium and hydrogen. For instance, it has been possible to raise the pressure to $P \approx 400$ MPa with a chamber volume of the order of 100 $\text{cm}^3$ (helium as the working gas) and an initial pressure of 10-25 MPa. The fraction of electrical energy used to increase the internal energy of the gas (efficiency) was $\eta = 0.8$.

With hydrogen as the working medium, it was possible to reach final pressures of up to 500 MPa at $\eta = 0.8$ in chambers with a working volume of the order of 100 $\text{cm}^3$ and initial pressures of 25-45 MPa. The pulse current was I = 1-2 MPa and the plasma temperature was $(4\text{-}5) \cdot 10^4$ K. The radiation from the column of plasma, which is nearly an absolute black body, is effectively absorbed near the column. As a result, the column expands and its internal energy grows. We must point out that the presence of metal vapor increases the efficiency of radiation absorption [1].

The discharge chambers of pulse plasma accelerators, which are being discussed extensively in the literature at present [6], should be classified as pulse plasmotrons. The discharge chambers of these devices are usually a polyethylene tube of diameter 2-5 mm, encased in steel walls, with electrodes introduced into it. The discharge results in ablation of the chamber walls and generation of a plasma jet. The plasma consists of partially ionized hydrogen, carbon, and $CH_2$ molecules. First hydrogen escapes as the jet flows out. The plasma jet velocity is 6-20 km/sec. This occurs at an electric current $I = 10^5$ A and a pressure of up to 5 kbar. The temperature in the discharge is 1.5-4 eV (in a number of cases the electron temperature was found to be higher than the temperature of the atoms).

An interesting property of pulse-flow plasmotrons is their ability to generate a high-pressure nonequilibrium plasma [5]. This applies primarily to the generation of a vibrationally nonequilibrium nitrogen plasma at pressures above atmospheric.

For instance, in [7] the temperature in the mixing chamber, measured by the iron, chromium, calcium, and sodium lines, was 0.25 ± 0.03 eV. The gas temperature did not exceed 0.13 eV. The vibrational temperature, measured in a supersonic channel on the given device, was close to the excitation temperature of metal atoms in the mixing chamber. Recombination of the dissociated nitrogen is one factor causing a nonequilibrium plasma to form. Moreover, because of the presence of metal vapor in the plasmotron chamber a vigorous exchange many occur between nitrogen molecules and excited metal atoms, since the cross section for this interaction is large.

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TABLE 1. Main Characteristics of Operating Pulse Plasma Generators

| Plasmotron | I, kA | U, kV | Gas | $P_0$, MPa | $P_f$, MPa | τ, msec | $T \cdot 10^{-3}$, K | Reference |
|---|---|---|---|---|---|---|---|---|
| IPP-3 | 300 | 0,6—2 | $H_2$, He, $N_2$, Ar | 0,1—2 | 10—200 | 0,5—2 | 2—20 | [1,2] |
| IMPP | 10—350 | 0,5—8,5 | $H_2$, He, $N_2$, Ar | 0,1—6 | 10—120 | 1,5—7 | 1,5—80 | [1] |
| IGPV | 100—1700 | 1,5—9 | $H_2$, He, $N_2$, Ar | 10—42 | 100—600 | 0,12—3 | 1,5—4,5 | [3] |
| REM | 130—300 | 0,5—5 | He | 10—30 | 100—600 | 0,5 | 5—10 | [4] |
| ÉDPL | 0,5—2 | 0,5—4 | $H_2$, He, $N_2$, Ar | 0,3—12 | — | 1—500 | 2—5 | [1,5] |
| MARR | 250 | 1,25 | $H_2$, $C_2H_4$ | — | 400 | 0,08—0,06 | — | [6] |

Having absorbed the energy of the quanta emitted by the arc, metal atoms at the boundary of the arc transfer it primarily to the molecular nitrogen, thus ensuring nonequilibrium heating of the gas outside the arc. If the arc temperature is above $10^4$ K, photoionization of the metal atoms outside the arc is possible. A fairly high concentration of electrons is formed because of the low concentration of metal atoms and the rather high probability of excitation of the atoms of the metal vapor far from the center of the arc. Estimates show that in high-power pulsed discharges the electron concentration inside the arc is $n_e = 10^{45}\text{-}10^{17}$ cm$^{-3}$. This ensures diffusion flow of a current $I = 10^3\text{-}10^4$ A and prevents contraction of the arc.

A Z-pinch discharge in helium and air at an initial pressure of 0.1-15 MPa was used in a number of studies [8] to obtain a dense plasma with a temperature of $10^5$-$10^6$ K and a pressure of up to $10^9$ Pa. The current increased initially at a rate of $6 \cdot 10^{11}$ A/sec and had a maximum amplitude of more than 600 kA. A low-inductance capacitor bank for a voltage of 50 kV was developed to accomplish this [9]. The discharge was initiated by the injection of a jet of helium plasma along the discharge axis from the central electrode.

In summary, the high-power pulse plasmotrons developed and built mainly as a result of the efforts of Soviet scientists are new universal sources of dense high-temperature plasma. Besides being used to solve a number of applied problems of high-speed aerodynamics and ballistics, such sources make it possible to pursue research in a new, little-studied area of science, the physics of dense relatively hot plasmas.

## NOTATION

I, arc current; U, arc voltage; $P_0$, initial pressure; $P_f$, final pressure; $T_{\Phi}$, mean mass temperature; $\eta$, efficiency; $n_e$, electron concentration.

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