CHOICE OF OPERATING CONDITIONS AND PLASMA
PARAMETERS OF A MAGNETOPLASMA COMPRESSOR

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The optimum operating conditions of a compact magnetoplasma compressor with
valved admission of the working gas have been found by experimental methods.

The parameters of the compression plasma flow in a magnetoplasma compressor (MPC) [1,
2] depend essentially on the maximum discharge current I_{max} and, other conditions being
equal, on how the working material is fed into the interelectrode gap. Pulsed admission
of gas into the discharge device is the most efficient way, which is used rather commonly
in research on plasma accelerators. In this case the choice of accelerator operating con-
ditions is decisive for the stability of the plasma flow and for the level of impurities
in the flow. Sufficiently simple and graphic criteria for choosing the optimum MPC oper-
ating conditions, however, do not exist at present.

Here we report the results of experimental studies on a compact MPC [3] with pulsed
(valved) admission of hydrogen, undertaken to ascertain the effect of the working-gas flow
rate on the behavior of the compression flow and its parameters. The experimental stand
consists of a vacuum unit, including a chamber of diameter 0.3 m and length 1 m with sys-
tems for evacuation and admission of the working gas, as well as a power supply consisting
of a sectioned bank of K 41-I7 capacitors with a total capacitance of 800 μF ($W_0 \lesssim$ 10 kJ;
here W_0 is the energy stored in the storage device) and a bank of the same kind of capaci-
tors with a capacitance of 300 μF to supply an electrodynamic valve. Each of the banks
was discharged to a corresponding load through its own IRT-3 ignitron discharger. The oper-
ation of the MPC, the system of valved operating-gas admission, and diagnostic equipment
was synchronized with a GI-1 six-channel delayed-pulse generator.

The discharge unit of the compact MPC is shown in Fig. 1. The inner copper electrode
was made as a truncated cone with an axial hole (diverter), while the outer electrode is a
cylinder formed by eight copper rods arranged symmetrically on a circle. A cylindrical
insulator with a developed surface is hidden in a pocket in a bearing flange and the effec-
tive (conical) part of the inner electrode is a considerable distance from it (compared to
an ordinary MPC). The working gas (hydrogen) was fed into the interelectrode gap by an
electrodynamic ring valve. To prevent the gas from spreading in the radial direction the
MPC discharge unit was enclosed in a casing of organic glass or quartz. Eighteen gas-inlet
holes are arranged symmetrically on a circle between the outer electrode and the casing to
ensure that the working gas is fed into the interelectrode gas from the anode side, which
favorably affects the stability of the emerging plasma flow. The indicated geometry of the
electrode arrangement of the MPC under the experimental conditions eliminates the possibil-
ity of the ionization zone being displaced toward the insulator during a discharge pulse.

The electrodynamic valve makes it possible to set a neutral-hydrogen flow rate of $\sim$ 3
to $\sim$ 12 g/sec in a pulse at a gas pressure of 1-3.5 atm in the volume beneath the valve and
a voltage of 1.5-3.5 kV in the valve capacitor bank. When the initial voltage of the energy
storage device is varied from 2 to 5 kV (while an additional resistance is introduced into
the discharge circuit), a discharge current of 30 to 120 kA (at the maximum) can be obtained
in the MPC.

The dynamics of discharge development in the MPC was studied with two high-speed SFR
light-beam recorders operating synchronously in the frame and continuous scanning modes. As
shown by the photographic scans, gas breakdown in the interelectrode gap occurs where the
gap is at its minimum. The leading edge of the plasma flow formed goes beyond the cut of the
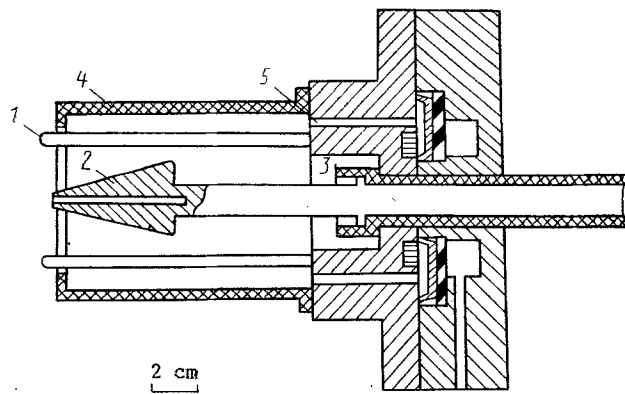
Fig. 1. Discharge unit of MPC: 1) rod anode;
2) cathode; 3) insulator; 4) casing; 5) gas
inlet hole.

inner electrode, which is the cathode in the first half-period, within 5-8 μsec from the onset of the discharge current. The trailing boundary of the ionization zone in the first 40 μsec is immobile and is at the narrowest part (critical section) of the accelerating channel. It then moves toward the channel exit with a velocity $\sim 10^5$ cm/sec. A stable compression plasma flow forms behind the cut of the inner electrode within $\sim$ 15 μsec after the discharge begins. The divergence and linear dimensions of the compression flow depend on the maximum discharge current and the mass flow rate of neutral hydrogen. For all of the MPC modes investigated the visible diameter of the flow is 0.5-1 cm and its length is 4-6 cm (the larger dimensions correspond to a higher $\dot{m}_0$, but the dependence of the linear dimensions on the current is more involved: as I_{max} grows the diameter of the flow decreases and its length increases, while the half-angle of the jet decreases from 20 to 5°). The maximum velocity of the plasma formations of the compression flow in the MPC, determined from continuous photographic scans with the slit of the SFR oriented along the axis of the electrode system, depending on the maximum discharge current and the mass flow rate of the gas is $(4-7) \cdot 10^6$ cm/sec. The compression plasma flow collapses by $\sim$ 70 μsec after the onset of the discharge current.

The plasma formations in the MPC were studied spectroscopically with an ISP-30 spectrograph as well as with an ISP-30 in conjunction with an SP-452 spectrochronograph. The image of the middle part of the accelerating channel with a length of 4 cm, starting from its critical section (the longitudinal axis of the image is parallel to the axis of the electrode system) was projected onto the spectrograph slit in measurements inside the discharge device of the MPC while the image of the cross section of the plasma formation a distance of 1 cm from the cut of the inner electrode was projected in studies of the plasma flow at the MPC exit. The 300-700 nm region of the emission spectra of the plasma exhibit mainly continuous radiation, lines of atomic hydrogen, and the most intense (resonance) lines of the atoms of elements that are components of the electrode material. At low gas flow rates the intensity of the lines of the elements of the electrode material increases and so does the number of lines.

The electron concentration n_e in the channel and in the compression flow was determined from the broadening of the H_β line as a result of the linear Stark effect. The relative error in the determination of n_e by the indicated method under the conditions of the experiment reaches $\sim$ 30% because of the existence of continuous radiation. Figure 2 shows how the electron concentration inside the channel varies as a function of the distance ℓ, starting from the critical cross section of the channel. The indicated values of n_e were averaged over the time of the entire discharge and along the line of sight, which as shown by calculations of the Stark profiles of the H_β line, leads to results that are underestimated in comparison with the maximum values [3]. The electron concentration of the compression flow from the half-width of the H_β line in the plasma emission spectrum in the cross section 1 cm away from the cut of the inner electrode is, e.g., $(0.7-2) \cdot 10^{17}$ cm^{-3} when the voltage varies from 2 to 4 kV. These values correspond to the interval from 10 to 20 μsec after the onset of the discharge and were averaged over the line of sight.

The electron temperature T_e in the plasma flow was determined from the relative intensity of the H_β and H_γ lines on the assumption of local thermodynamic equilibrium (analysis
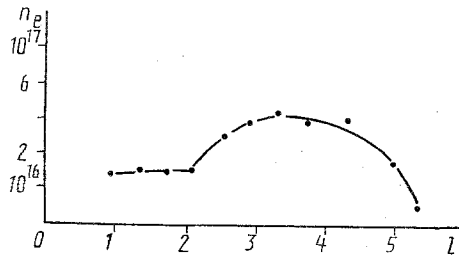
Fig. 2

Fig. 3

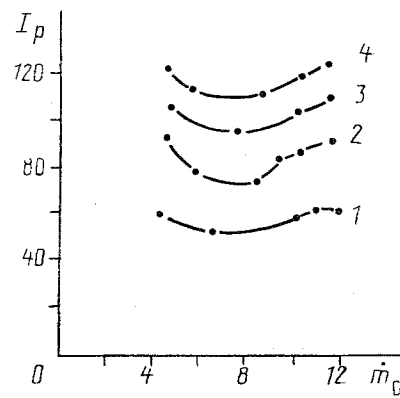Fig. 2. Variation of the electron concentration inside the channel, n_e, cm^{-3}; ℓ, cm.

Fig. 3. Dependence of the maximum discharge current on the mass gas flow rate: 1) $U_0 = 2$ kV; 2) 2; 3) 4; 4) 5. I_p, kA; $\dot{m}_0$, g/sec.

of the results, with allowance for the fact that the optically thin plasma was inhomogeneous and transient, enabled us to conclude that local thermodynamic equilibrium exists in the compression flow at $n_e > 1.5 \cdot 10^{17}$ cm^{-3} ($T_e \sim 1$ eV)). At a hydrogen mass flow rate $\dot{m}_0 \sim 10$ g/sec and a maximum discharge current ~ 60 kA the electron temperature in the flow distance of 1 cm from the cut of the cathode is $\sim (10-12) \cdot 10^3$ K. We recall that the indicated values were averaged over the line of sight and the exposure time.

The oscilloscope traces and the discharge voltage in the MPC, with an oscillatory nature and strong attenuation, were recorded with a calibrated Rogowski loop and a compensated RC divider. The relative error in the calibration of the loop and the divider is 15%. From the oscilloscope traces we determined the instantaneous power and the energy input into the discharge, which enabled us to calculate the energy efficiency of the system, which was construed as the ratio of the energy input into the discharge to the initial energy storage in the storage device. The energy input into the discharge ended mainly by the end of the first half-period of the discharge current (~ 70 μsec). For all the MPC operating regimes studied the energy efficiency by that time was 0.6-0.8 (the higher value corresponds to lower mass flow rates of the working gas). The current-voltage characteristics showing the dependence between the current and the current during one discharge from 20 to 60 μsec (when the transient processes in the MPC ended and the plasma flow was in the stable quasisteady state) are nonlinear for all the operating regimes studied and are power-law relations with an exponent of ~ 2.

We construct the dependence of the maximum discharge current in the MPC on the mass flow rate $\dot{m}_0$ of the neutral hydrogen, using the initial voltage U_0 of the energy storage device as the variable parameter (Fig. 3). Returning to the plasma velocity measurements described above, we note that the maximum values of the indicated quantity for each U_0 are reached at flow rates $\dot{m}_0$ such that $I_{max}(\dot{m}_0)$ are smallest. The increase in the maximum value of the current (at a fixed U_0) with decreasing $\dot{m}_0$ in the region of low gas flow rates, according to spectroscopic studies, is due to electrode erosion, causing the effective mass of the working substance to grow and, therefore, the plasma velocity to decrease. Under the same conditions the current increases with rising $\dot{m}_0$ in the region of large flow rates, mainly because the number of carriers increases as a result of the growth of the particle concentration and the volume of the gas-discharge plasma, which also causes the plasma velocity to decrease. MPC operating regimes for which $I_{max}(\dot{m}_0)$ are smallest, therefore, are the most effective from the standpoint of obtaining the maximum parameters of the compression plasma flow at a fairly low level of impurities.

Experimental studies of a compact MPC with valved admission of hydrogen, therefore, have shown that over a wide range of initial parameters, for which compression flow is established, electrotechnical measurements for each U_0 provide a basis for making a fairly simple choice of the optimum MPC operating regimes, which give relatively high plasma-flow parameters with the minimal impurity content for such systems.

NOTATION

MPC, magnetoplasma compressor; W_0, energy storage in the energy storage device; $\dot{m}_0$, mass flow rate of neutral hydrogen: I_{max}, maximum discharge current; n_e, electron concentration; ℓ, distance from critical cross section; T_e, electron temperature; U_0, initial voltage of storage device.

LITERATURE CITED

1. A. K. Vinogradova and A. I. Morozov, Physics and Application of Plasma Accelerators [in Russian], Minsk (1974).
2. A. I. Morozov and A. P. Shubin, Itogi Nauki Tekh. Fiz. Plazmy, 5, 178-260 (1987).
3. L. Ya. Min'ko, V. M. Astashinskii, G. I. Bakanovich, and A. M. Kuz'minskii, Vesti Akad. Navuk Belorus. SSR, Ser. Fiz.-Mat. Navuk, No. 2, 46-50 (1986).