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LABORATORY TECHNIQUES

Pulse Gas Valves For Plasma Injectors

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Abstract—Pulse gas valves for "anode ionization chamber" (AIC) and "input ionization chamber" (IIC) plasma injectors and features of their operation are described. The IIC and AIC plasma injectors are used for generation of primary plasma in the KSPU Kh-50 quasi-stationary strong-current accelerator. The results of studying basic gas-dynamic and electrical characteristics of the pulse gas valves are presented.

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INTRODUCTION

Owing to creation of the ITER experimental thermonuclear reactor, a problem of selecting materials for its energetically most loaded elements acquired a special importance. Elements of its diverter channel will be subjected to anomalously high thermal and corpuscular loads, created by the high-energy plasma flows due to disruptions of the current, vertical shifts of the plasma filament, and instabilities of the edge-localized-modes (ELMs) type. In this case, the energy load on elements of the diverter may reach 1–10 kJ/cm^2 within ~1–10 ms [1].

In this connection, it is necessary to study how high-energy plasma interacts with the surface of the materials of the most loaded elements of the ITER in conditions that are maximally close to the expected ones in the thermonuclear reactor.

These modeling experiments are performed on the KSPU Kh-50 quasi-stationary strong-current accelerator, Institute of Plasma Physics [2, 3]. The plasma flows that are close in their parameters to the expected ones in the ITER (the energy flow density is 3 kJ/cm^2; the total content of the energy flow is 520 kJ, when the pulse duration is 270 μs) are obtained on this accelerator [4–6].

These plasma parameters were attained owing to the matched and optimized operation of the system of plasma injectors (input ionization chamber (IIC) and anode ionization chamber (AIC)), which generate the primary plasma and transmit it to the KSPU Kh-50 basic accelerating channel. Each channel solves its own specific problems. Therefore, the valves of the working substance are constructively different.

PULSE GAS VALVE OF THE INPUT IONIZATION CHAMBER

The pulse electrodynamic gas valve is designed and manufactured to supply the substance gas into the interelectrode space of the IIC plasma injector (Fig. 1).

Locking plate *2* is concentrically placed in housing *1* of the valve. In the closed position, its tightening belts rest on gasket *3* of saddle *4*. Plate *2* is installed on the tip of rod *5* and fixed by nut *6*. Rod *5* has an axial channel, through which the working gas is supplied to booster cavity *7*, having a 123-cm^3 volume. In this cavity, the gas is accumulated before the inflow into the ionization zone of the IIC.

Rod *5* is sealed by tightening assembly *8* so that rod *5* moves, preserving air tightness. Control electromagnetic coil *9*, D16T aluminum alloy reflector *10*, and elastic shock absorber *11* are located concentrically to it on the opposite end of rod *5*. The force of compression of shock absorber *11* is regulated by screw *12*.

When a current pulse is applied to the winding of coil *9*, the magnetic field of the coil induces eddy currents in reflector *10*. As a result, it is thrown away from the coil by rod *5*. Plate *2* is moved away from the gaskets, freeing inlet channels *13*.

The coil location outside the sealed cavity simplifies the design of the valve and facilitates the operating conditions, although this leads to increasing the relocated mass. With this layout, it is not required to match overall dimensions of the coil and electrodes of the plasma injector. This allows one to increase the outer diameter of the electromagnetic coil and, thus, increase the electrodynamic force. This compensates for the influence of inertia, related to an increase in the mass of the locking assembly.

In the valve, the parameters of the gas flow, admitted into the discharge channel, are regulated by chang-

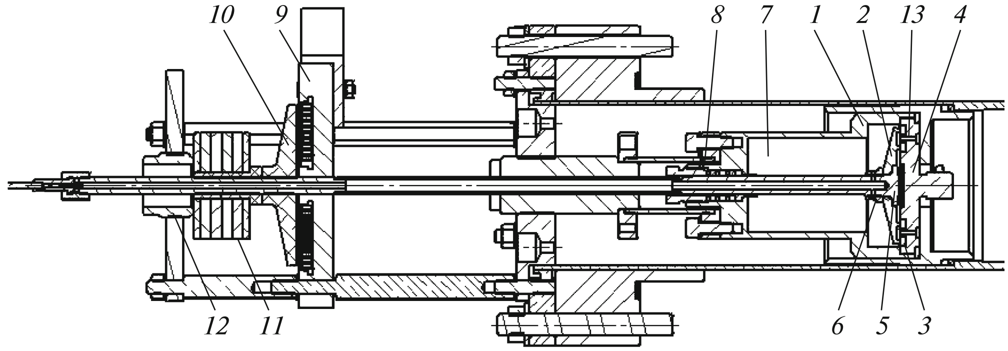

Fig. 1. Pulse gas valve of the IIC: (*1*) housing of the valve; (*2*) locking plate; (*3*) gaskets; (*4*) saddle of the valve; (*5*) rod; (*6*) nut; (*7*) booster cavity; (*8*) tightening assembly; (*9*) electromagnetic coil; (*10*) reflector; (*11*) shock absorber; (*12*) screw; and (*13*) gas inlet channels.

ing the control current, the initial gas pressure in the booster cavity, and the force of compression of the elastic shock absorber.

STUDIES OF GAS-DYNAMIC AND ELECTRICAL CHARACTERISTICS OF THE PULSE GAS VALVE OF THE IIC

The study of the gas-dynamic characteristics of the working-substance valves was performed using piezoelectric pressure transducers (the speed of their operation is 2.5–3 μs). The current value in the winding of the coil was measured using calibrated Rogowski coils. The volume of the gas, which is admitted by the pulse valve of the working substance for one pulse, was determined by the calculation method after the VT-3 vacuum-gauge measurement of the pressure difference in the vacuum chamber of the plant before and after the inflow.

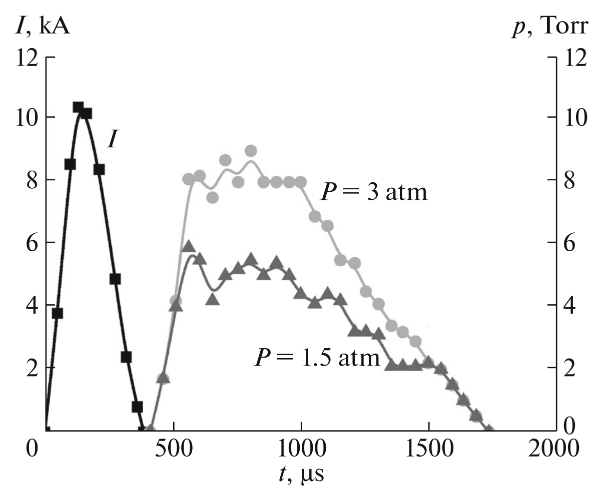

Fig. 2. Time dependences of the current pulse in the winding of the control electromagnetic coil of the pulse gas valve of the IIC for a voltage of 1.75 kV at the power-supply bank and a gas-pressure pulse for nitrogen at the initial pressure of the working gas in the booster cavity of 1.5 and 3 atm.

Figure 2 shows the time dependences of the current pulse in the winding of the control electromagnetic coil of the pulse gas valve of the IIC for a voltage of 1.75 kV at the power supply bank and a gas pressure pulse during the nitrogen inflow at the initial pressure of the working gas in the booster cavity of 1.5 and 3 atm. The gas pressure in the flow was measured at a distance of 400 mm from the gas inlet channels.

This is apparent from Fig. 2 that for the stated operation modes of the cutoff valve, 600–1000 μs is the time gap, when the nitrogen pressure in the flow is close to its maximum and, in addition, does not substantially change.

Therefore, it is expedient to switch-on the voltage between the electrodes of the IIC for the discharge formation and plasma generation with a delay of ~600 μs after the supply of a current pulse. In this case, the ionization of the working gas occurs at the maximal pressure and is relatively stable during the plasma existence time.

It is important both for creation of the leading edge of the gas pulse with the optimal gas-dynamic parameters and formation in the gas flow of an optimal pressure gradient along the radius and length of the accelerating channel for the timely supply of the plasma flow with lacking carriers of the discharge current. This injection scheme of the working gas allowed us to eliminate the near-electrode potential jump and, as a result, obtain a plasma flow with high energy characteristics.

The influence of the voltage across the winding the winding of the control coil and the initial pressure of the working gas in the booster cavity of the gas valve on the hydrogen inflow volume is shown in Fig. 3.

It follows from these dependences that an increase of the voltage across the winding of the coil of the gas valve leads to an increase in the volume of the working-gas inflow.

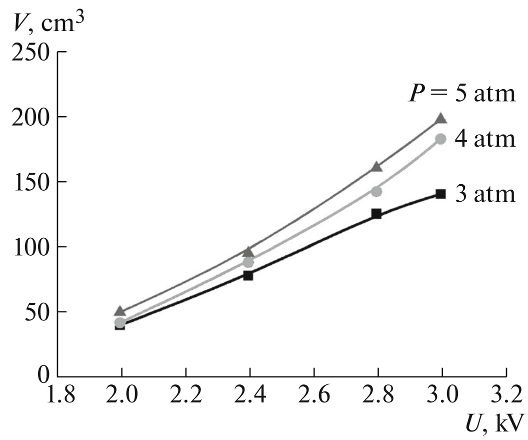

Fig. 3. Dependences of the volume of the hydrogen inflow through the gas valve of the IIC on the voltage across the winding in the winding of the control coil at different initial pressures P of the gas in the booster cavity.

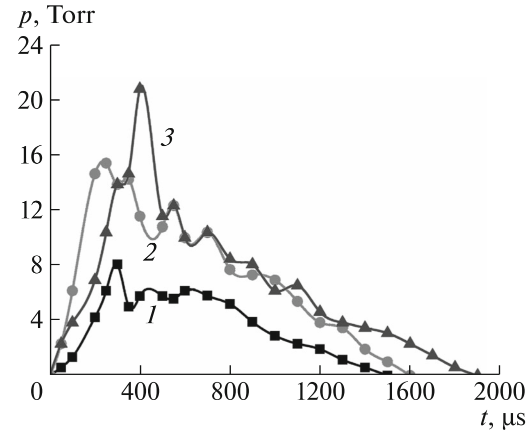

Fig. 4. Time dependences of the gas-pressure pulse for hydrogen at the initial pressure of the working gas in the booster cavity of the IIC gas injector of 1.5 atm, when the variation of the voltage at the power-supply bank of the coil of the IIC gas valve is (*1*) U = 1.5, (*2*) 2.0, and (*3*) 2.5 kV.

Figure 4 shows the time dependences of the gas-pressure pulses for hydrogen at the initial pressure of the working gas in the booster cavity of 1.5 atm during variation of the voltage at the power supply bank of the control coil of the gas injector. The duration of the gas pulse increases with an increase in the voltage at the coil terminals. For example, when the voltage is 1.5 kV, the duration of the gas pulse is 1500 µs, and, when it is 2.5 kV, the gas-pulse duration is 1900 µs. In all the modes, a pressure peak with a duration of 40–50 µs is observed at the beginning of the gas pulse after which the hydrogen pressure in the flow decreases.

Figure 5 shows the dependence of the maximal pressure of hydrogen in the flow on the supply voltage of the coil of the gas injector. One should note that this dependence is close to linear.

The dependences, shown in Figs. 4 and 5, allow one to select the optimal operating mode of the gas valve. For example, for the plasma-dynamic systems with a short pulse (10–20 µs) and high pressure of the working gas in the flow (of "plasma gun" type) the operation of the injector with a voltage of 2.5 kV at the coil is optimal. In this mode, the section of the gas pulse with the peak pressure value is used to generate plasma.

For generation of a longer plasma pulse it is expedient to use the coil voltage varying from 1.5 to 2 kV (the amplitude of the current in the winding of the coil is 9–10 kA, respectively). In these modes, the gas pulse has pronounced sections of the relatively stable pressure, which is close to the maximum.

PULSE GAS VALVE OF THE ANODE IONIZATION CHAMBER

After the ionization of the working substance in the discharge space of the accelerator, the positively charged ions start moving towards the cathode. Due to this fact, a zone with the deficit of positively charged ions and, hence, with the excess of negatively charged particles is formed near the surface of the anode. Zones with the negative charge are formed namely here. This forms a near-anode potential jump. As a result, the symmetry of the plasma flow is violated, thus leading to instability of the ionization zone of the working gas and preventing the efficient conversion of the storage energy into the kinetic energy of the plasma flow [5]. To overcome this drawback, substantially new approaches to organizing regular plasma flows and developing adequate designs of plasma-dynamic systems and their valves of the operating substance are necessary.

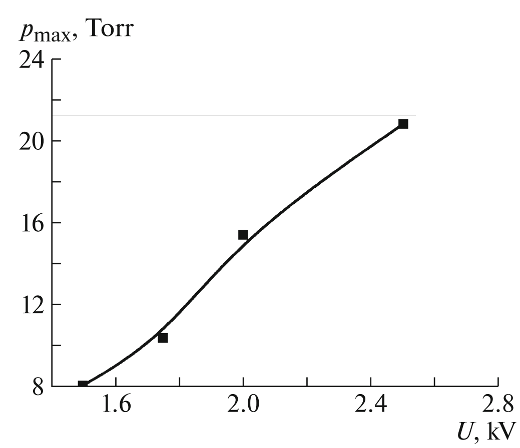

Fig. 5. Dependence of the maximum pressure of hydrogen in the flow on the voltage at the power-supply bank of the coil of the IIC gas injector.

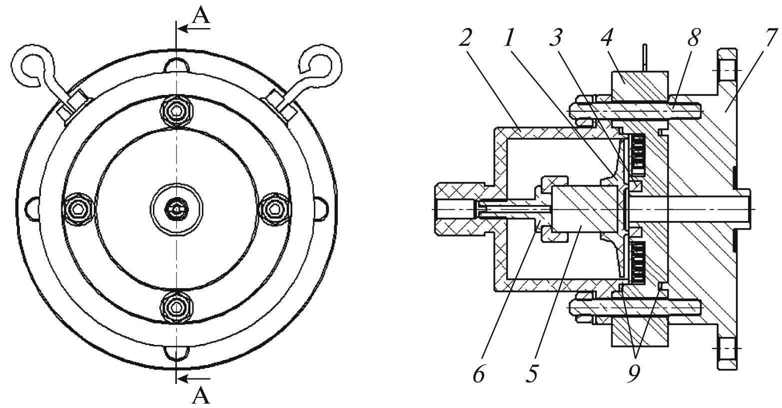

Fig. 6. Design of the pulse valve of the working substance of the AIC with the axial inflow: (*1*) locking plate; (*2*) housing of the valve; (*3*) gasket; (*4*) electromagnetic coil; (*5*) elastic shock absorber; (*6*) screw; (*7*) flange; (*8*) stud; and (*9*) gasket.

The basic purpose of the AIC is the generation of the primary plasma and its supply to the near-anode region of the KSPU Kh-50 accelerating channel for its provision with deficient carriers of the discharge current and elimination of the near-anode potential jump [4, 5].

Some specific requirements are imposed on the AIC plasma injector. The basic requirements firstly include the provision of a stable plasma flow, ensuring a sufficient mass flow during at least 400 μs, which approximately corresponds to the duration of the plasma generation in the KSPU Kh-50 basic accelerating channel. Secondly, the rate of the plasma flow, generated by the AIC, should not be lower than the rate of the leading edge of the basic discharge of the KSPU Kh-50 accelerator. Otherwise, the plasma flow, generated by the AIC, can not efficiently feed the near-anode zone.

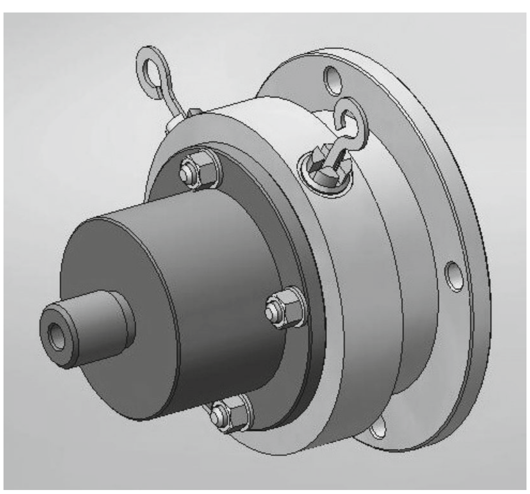

Fig. 7. Outward appearance of the pulse valve of the working substance of the AIC.

Figure 6 shows the design of the gas valve of the AIC, and its outward appearance is shown in Fig. 7. Locking plate *1* is placed in housing *2*. In the closed position, it rests by its tightening belt on gasket *3*, which is placed in the ring groove of control electromagnetic coil *4*. Plate *1* is pressed to gasket *3* by shock absorber *5*. The force of compression is regulated by screw *6*. Elastic shock absorber *5* is centered in grooves of plate *1* and adjusting screw *6*. Housing *2* and coil *4* are jointed to flange *7* by studs *8* and sealed by gaskets *9*.

Figure 6 shows the gas valve variant with the axial gas supply. By changing the embodiment of gas inlet channels, the injector variant with a ring inlet was created, when the operating gas is supplied to the discharge space of the injector in the form of an annular jet. In addition, the annular jet is injected along the surface of the outer electrode (in this case, anode). The supply scheme of the operating gas is preferable, if a problem of eliminating the near-anode potential jump is solved. Different injection schemes of the working gas into the accelerating channel of the plasma-dynamic system is an important factor of controlling the working gas dynamics in the accelerating channel, and, hence, the parameters of the plasma flow and their optimization.

One should note that this construction scheme of the pulse gas valve ensures a higher speed of operation, since here the only moving element is the locking plate, directly on which the control electromagnetic coil acts.

There is a limitation of the initial pressure value of the working gas in the booster cavity for most gas valves with an electrodynamic drive. This factor makes it impossible to use them in high-power plasma-dynamic systems, where it is necessary to supply gas into the discharge space with a high rate and pressure, simultaneously ensuring the necessary mass flow of the working gas. In the gas valve of the AIC, this pressing force is substantially decreased, since the gas pressure acts only on a 12% area of the locking element.

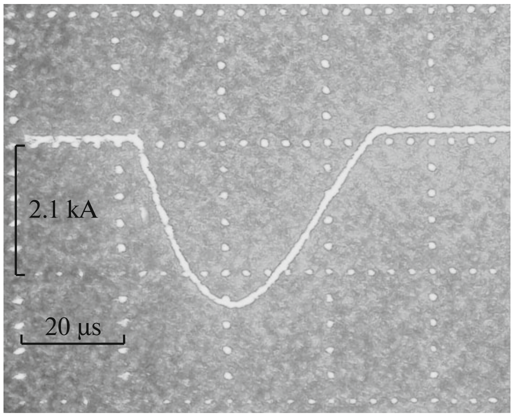

Fig. 8. Typical oscillogram of the current in the winding of the control electromagnetic coil of the pulse valve of the working substance of the AIC (voltage at the bank of capacitors $U = 0.7$ kV, and the capacitance of the bank is 200 μF).

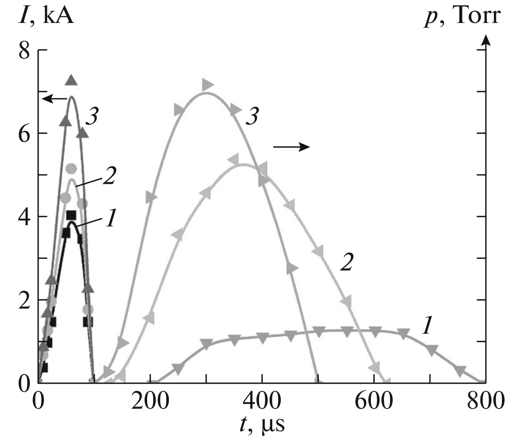

Fig. 9. Time dependences of the current in the winding of the gas-valve control coil of the AIC (I) and pressure of hydrogen in the flow (p) at the initial gas pressure in the booster cavity of 1.5 atm and variations of voltages at the bank of capacitors (U): (*1*) 0.5, (*2*) 0.6, and (*3*) 1 kV.

On the remaining 88% area, the gas-pressure forces from opposite sides of the locking element mutually balance each other, allowing one to operate with higher initial pressures of the working gas.

GAS-DYNAMIC AND ELECTRICAL CHARACTERISTICS OF THE PULSE VALVE OF THE AIC

Figure 8 shows a typical oscillogram of the current in the winding of the electromagnetic coil of the valve. The maximum current in the coil winding is 2.8 kA. The duration of the first half-period of the current pulse, during which the gas valve opening occurs, is about 100 μs.

The power supply system of the valve is designed so that the control current rapidly attenuates and the second and subsequent half-periods of the current do not exert the substantial influence on the locking element of the gas valve.

Figure 9 shows the time dependences of the current in the winding of the control coil, hydrogen pressure in the flow p at the initial gas pressure in the booster volume of 1.5 atm, and variation of the voltage at the bank of capacitors. The pressure of the working gas in the flow was measured by the piezoelectric pressure detector at a distance of 220 mm from the inlet channel.

The substantial influence of the current in the valve coil on the shape of the gas pulse and hydrogen pressure in the flow is shown in Fig. 9.

Figure 10 shows the time dependences of the current in the coil and gas pressure at the same voltage of 1 kV for the initial gas pressure of 1.5 and 2 atm in the booster cavity of the AIC.

The influence of the voltage at the winding of the coil on the nitrogen and hydrogen inflow is shown in Fig. 11. The dependences of the integral gas inflow of the gas valve of the AIC on the voltage at the power-supply bank of the control coil are given at the initial pressure of the working gas in the booster cavity of 1.5 atm. It is possible to distinguish two characteristic sectors in the curves of the nitrogen and hydrogen inflow. The dependences of the inflow are close to linear for voltages of up to 1 kV. When the voltage increases more than 1 kV, the curves have a sharp bend towards reduction of the inflow, i.e., there is a tendency towards saturation. This occurs due to the fact that at voltages over 1 kV, the booster cavity of the valve is virtually completely freed of gas within the pulse time.

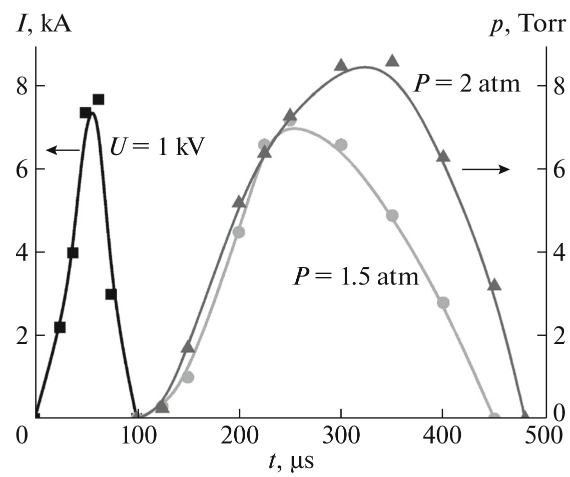

Fig. 10. Time dependences of the current I in the winding of the coil and gas pressure p in the flow at the same voltage $U = 1$ kV for the initial gas pressures $P = 1.5$ and 2 atm in the booster cavity of the AIC.

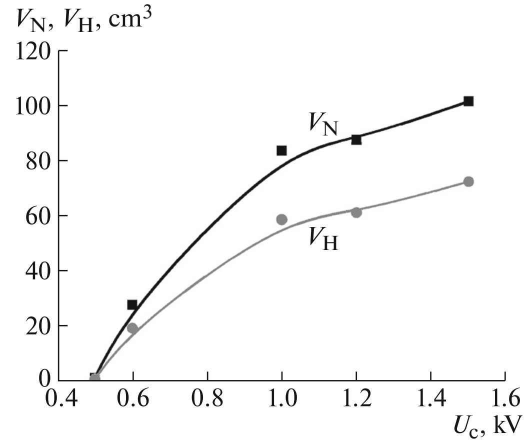

Fig. 11. Dependences of the volume of nitrogen and hydrogen (at the atmosphere pressure) that are injected by the gas valve of the AIC for one pulse on the voltage at the terminals of the control electromagnetic coil at the initial gas pressure in the booster cavity of 1.5 atm.

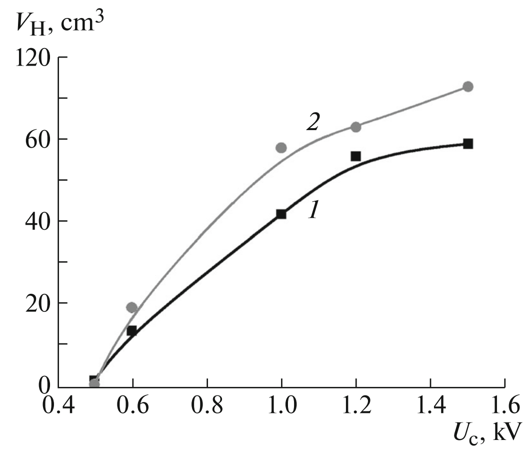

Fig. 12. Dependences of the hydrogen volume (at the atmosphere pressure) that is injected by the gas valve of the AIC for one pulse on the voltage at the terminals of the control coil at the initial gas pressures in the booster cavity of (*1*) 1 atm and (*2*) 1.5 atm.

Figure 12 shows the dependences of the hydrogen volume (at the atmospheric pressure), admitted by the gas valve of the AIC during one pulse, on the voltage at the control coil terminals, when the initial pressures in the booster cavity are 1 and 1.5 atm.

One should also stress that the described gas valve allows one to admit the working gas in a wide range of 1 to 75 cm^3 per pulse (at the atmosphere pressure) for hydrogen and 1 to 100 cm^3 for nitrogen. It can be used both in high-power plasma-dynamic systems, in which the duration of the plasma generation is hundreds of microseconds, and in systems with a short pulse and small mass flow of the working gas, where the duration of the flow generation is only several microseconds.

The performed studies of the basic electrical characteristics of gas valves and dynamics of the gas-flow generation open up possibilities for the efficient matching of the gas injection processes and development of the discharge in the accelerating channel of the plasma injectors. In the optimal case, the ionization of the working gas in the discharge gap occurs at the moment, when the flow of the plasma-forming gas has the maximal pressure and is stable during the whole discharge existence time in the plasma accelerator.

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