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INCREASING PRESSURE DIFFERENCE VIA A GAS-DYNAMIC WINDOW FOR ELECTRON-BEAM EXTRACTION

L. N. Orlikov and N. L. Orlikov

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The functioning of a gas-dynamic window designed as an evacuation chamber with orifices 1 mm *in diameter for electron-beam extraction from vacuum* (10 Pa) *into the atmosphere is analyzed. An increase pressure difference is attained due to the ejecting effect arising when the gas flows over an element of the gas-dynamic window with pressure taps in the wall. A method for calculating the area of the pressure taps is presented.*

In order to extract electron beams from vacuum into the atmosphere, gas-dynamic windows [1–4] are used, designed as chambers with independent gas pumping and elements with orifices for electron-beam extraction. The operation of such devices, however, requires high-capacity vacuum pumps in order to maintain the pressure difference between the electron source and the gas chamber (5–10 kW per 1 mm^2 of the outlet-orifice area) [5–7]. The problem of beam extraction can be solved by employing gas-discharge electron sources operating under forevacuum [3, 4, 8], and also by using gas-dynamic effects for increasing the pressure difference via the gas-dynamic window.

Figure 1 shows schematically an electron source based on a high-voltage glow discharge with a two-stage gas-dynamic window. The source consists of a cold aluminum cathode and anodes between which an accelerating potential is uniformly distributed. With the pressure in the source equal to 1–10 Pa, a negative potential (up to 100 kV) is applied to the cathode. A high-voltage glow discharge is formed between the cathode and anodes. Ions from the glow-discharge plasma are attracted to the cathode. Electrons are knocked out of the cathode by ion bombardment. The electron beam with an amperage up to 100 mA is focused by the magnetic lens in the orifices of diameters d_2 and d_1 in the elements of the gas-dynamic window and is directed to the chamber with a pressure $P_{\rm ch}$. The gas flow from the chamber between the window elements (at the first stage of the window) has the form of a supersonic jet with the Mach disk and barrel shock wave. The pressure difference is determined as the ratio of the pressure in the chamber $P_{\rm ch}$ to the pressure at the second stage of the gas-dynamic window (in the electron source) P_2. In order to minimize the electron-beam losses in the gas, it is important to reduce drastically the distance h between the edges of the window elements at the minimum pressure in the electron source. In the course of the experiment, it has been found that, on using elements in the form of sharp-edged tubes, this condition is satisfied when the value of h is equal to the distance X_m to the Mach disk. The quantity X_m is given by the expression [9]

$$X_m = 0.7d_1(kP_j/P_1)^{0.5}, \tag{1}$$

where k is the ratio of specific heats, P_j is the pressure on the exit cross-section of the orifice, and P_1 is the pressure between the window elements.

Figure 2 shows schematically the gas flow in a two-stage gas-dynamic window formed by sharp-edged elements. Analyzing the experimentally obtained pressure distribution over the surface of the second stage of the window, we can conclude that the stagnation pressure P^* at the inlet of the window element is 5–6 times as high as the pressure P on its outer surface. The side pressure taps of diameter d^* in the element of the second stage of the window make it possible to evacuate part of the gas from the outlet orifice to the first stage of the window

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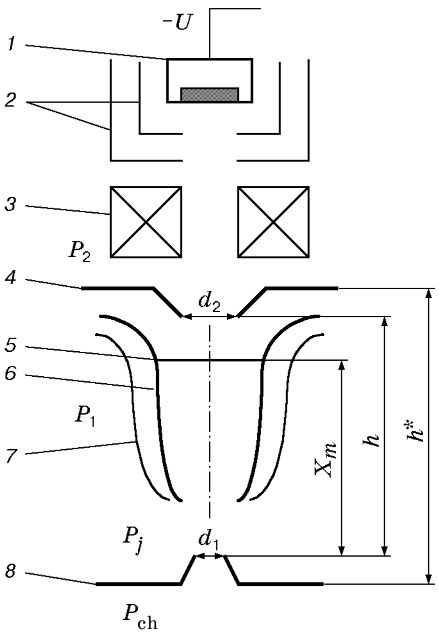

Fig. 1. Schematic of an electron source with a gas-dynamic window: 1) cathode; 2) anodes; magnetic lens; 4, 8) elements of the gas-dynamic window with orifices of diameters d_2 and d_1, respectively; 5) Mach disk; 6) barrel shock wave; 7) jet boundary.

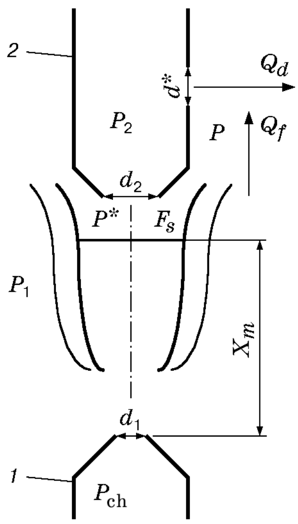

Fig. 2. Gas flow pattern in a gas-dynamic window with side orifices: 1 and 2 are sharp-edged elements.

due to the pressure difference on the walls of the element. This results in the increased pressure difference in the gas-dynamic window, which does not require boosting the capacity of pumping facilities.

For practical application of this method, the area of side orifices and their positions should be determined, as well as the amount of the gas being evacuated. The system can be readily analyzed on the basis of the general ejection equation [9]

$$n = \frac{1}{Na\theta^{0.5}} \frac{q(\lambda)_d}{q(\lambda)_f}, \tag{2}$$

where the ejection ratio $n = Q_d/Q_f$ is the ratio between ejected and ejecting fluxes, N is the pressure difference on the side orifice, a is the geometrical parameter (the ratio of the area of side orifices F^* to the area of the jet passing over the element), θ is the ratio of temperatures of ejected and ejecting jets, $q(\lambda) = [(k+1)/2]^{1/(k-1)}\lambda \times[1-(k-1)/(k+1)\lambda^2]^{1/(k-1)}$, and λ is the flow-velocity coefficient (the ratio of the flow velocity to the velocity of sound in the gas at rest); the subscripts d and f correspond to the ejected and ejecting gas flows.

A simplified formulation may be presented for practical calculations, making use of a one-dimensional model of exhaustion of a supersonic underexpanded jet and special features of its interaction with a sharp body.

For most of the practically implemented devices, the pressure difference at each stage of the window does not exceed two or three orders of magnitude. In this case, the internal diameter of the jet obtained from the Mach disk diameter is almost 10 times as large as the pressure-tap diameter d_1 [9]. In visualizing the gas flow in the glow discharge, the authors found out that a flow past an element occurs without separation of the Mach disk, if the height of the element (the distance from the base to the edge) is greater than that calculated from Eq. (1) and the external (outside) diameter is smaller than the Mach disk diameter. Under these conditions, no significant changes in the Mach disk wake occur, and the area of the jet around the side orifices can be taken to be equal to the area of the jet at the level of the Mach disk. For a tube-shaped element, the gas-flow velocity on its external surface can be assumed to attain the sonic velocity, and the ratio of the jet temperatures on either side of the side orifice is negligible. Consequently, we obtain $\lambda = 1$, $q(\lambda)_f = 1$, and $\theta = 1$ [9].

Pitot-tube measurements show that the stagnation pressure P^* and the static pressure at the inlet of the second stage of the window are comparable: $P^* \approx P_2$, and the pressure on the outer side surface of the element is close to the pressure P_1 between the elements: $P \approx P_1$. Therefore, it would be more feasible to put the side pressure taps near the orifice edge d_2.

Even when the ratio of pressures on the side wall is $P/P^* < 0.528$, the gas leaves the side orifices with the sonic velocity. A sound ejector is provided on the side orifice, for which the possible pressure increase under flow choking is $P^*/P_1 = 3.55$ [9]. Accordingly, the pressure difference on the side orifice approaches this value ($N \approx P^*/P_1$).

Equation (2) can be reduced to $n = 1/(3.55a)$. The experimental results show that this relation holds for gas-dynamic windows, if the pressure values at the stages are relatively high and the areas of the side orifices and jet area ($a = 1$) are comparable as well as the pressures. For the two-stage window under consideration, the minimum pressure in the electron source should be maintained. It can be attained with the minimum values of n and a.

The limitingly small value of the geometrical parameter can be obtained by analyzing the jets under the critical gas outflow through the orifices. The ejecting jet formed around an element at the window inlet is given by the relation employed in vacuum technology [10] for a viscous gas flow:

$$Q_f = 200F_1(P_{\text{ch}} - P_1). \tag{3}$$

At the inlet of the second stage of the window the gas Flow is

$$Q_2 = 200F_2(P_1 - P_2) \tag{4}$$

(the pressures P_1 and P_2 can be obtained from the ratio of the flow to the pumping-out speed [10]). The ejected gas flow through the side orifices of the element can be found in a similar manner:

$$Q_d = 200F^*(P^* - P_1). \tag{5}$$

In practice, the last term in brackets in Eqs. (3)–(5) is ignored because of its negligible smallness in comparison with the first term.

The part of the flow directed through the side orifices with allowance for the pressure increase ($P^* \approx 3.55P_1$) is obtained from the ratio of Eqs. (5) and (4): $Q_d/Q_2 = F^*/F_2 = 0.71$. The ejection coefficient can be also found from the ratio of Eqs. (3) and (5): $n = Q_d/Q_f = F^*/F_s$, where F^* is the area of the side orifices and F_s is the jet area at the Mach disk level. In practical applications, with the Mach disk diameter 10 times as great as the orifice diameter, the ratio of the area of the side orifices to the jet area is obtained from the relation $a = F^*/F_s \approx 10^{-2}$.

The efficiency of the pumping-out elements with side orifices has been experimentally tested using a gas-discharge electron source with a gas-dynamic window [4]. The electron source was evacuated by an VN-1 vacuum pump with a pumping speed of 10 dm^3/sec, and the window was evacuated by a VN-7 pump with a speed of 45 dm^3/sec. The diameter of the pressure taps was 1 mm. Five orifices 0.6 mm in diameter were located in the element of the second stage of the window. The distance between the element edges was $h = 9$ mm, and the element bases were $h^* = 30$ mm apart.

Figure 3 shows the pressure in the electron source versus the pressure in the chamber under a voltage of 60 kV and amperage up to 30 mA. It is evident that a lower pressure in the electron source is attained in the window with side orifices. It was found that the number of the side orifices depends on the system-operation mode. A larger area of the side orifices results in an increase in the ejection coefficient. However, it also leads to

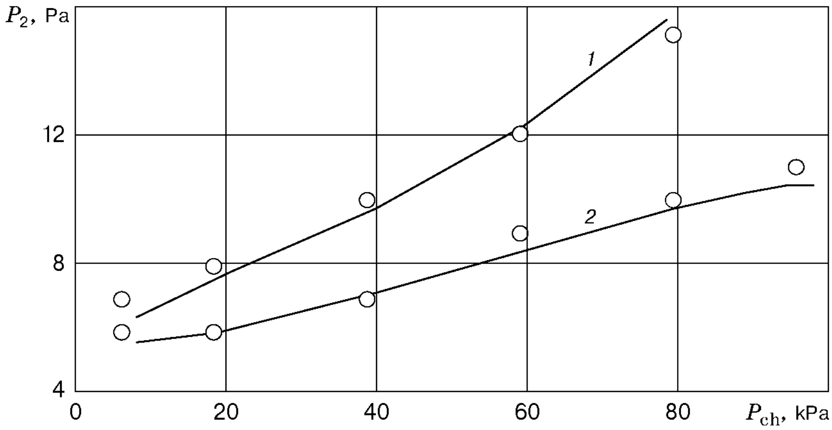

Fig. 3. Pressure in the electron source versus the pressure in the chambers ($d_1 = d_2 = 1$ mm) without side orifices (curve 1) and with five side orifices 0.6 mm in diameter (curve 2).

an increase in ejection pressure and a smaller pressure difference between the source and the space between the elements. Direct measurements of the gas discharge show that the amount of the gas entering the second stage of the window is lower by a factor of 80–100 than the amount of the gas introduced into the first stage. The pressure change at the first stage of the window due to the gas incoming through the side orifices was not detected because of the relatively small change in the gas amount and the high speed of gas pumping out of the first stage of the window. However, the amount of the removed gas occupies a volume greater by the same factor as the decrease in the second-stage pressure in comparison with the first one. Therefore, a small change in the gas discharge at the inlet in the second-stage element orifice changes significantly the pressure in the electron source.

Thus, the use of a construction with side orifices in the second-stage element enables one to raise the pressure difference from $4 \cdot 10^3$ to 10^4 and to reduce the required speed of the pumping system from 5 to 1.5 kW per 1 mm^2 of the outlet-orifice area. Under a constant pressure difference, the area of the outlet orifice for beam extraction can be increased two or three times without raising the speed of the pumping facilities.

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