IMPROVING THE EFFICIENCY OF GASDYNAMIC WINDOWS FOR ELECTRON BEAM EXTRACTION

L. N. Orlikov and E. V. Chikin

UDC 533.9.082

1. Devices for extracting electron beams and conveying them to a gas at medium or high pressure are now being used to an ever increasing extent in electron-beam technology [1], quantum electronics [2], and gasdynamics investigations [3]. Such devices are based mainly on two methods: beam extraction through a thin metallic foil and extraction through a gasdynamic window (GDW) [4], which, in its simplest form, consists of a system of coaxial diaphragms, where the gaps between the diaphragms are evacuated. It is sometimes more advisable and advantageous to use a GDW than a foil. This applies mostly to cases where it is necessary to ensure reliable and trouble-free continuous operation of the device in extracting powerful beams with a relatively low energy (up to 100 keV). At the same time, GDW's have not been utilized widely in technology and scientific research because of a number of technical difficulties encountered in using them. The main difficulty is the necessity of using high-efficiency, cumbersome, and power-consuming evacuation devices for producing the required pressure drop between the electron gun and the operating chamber to which the beam is conveyed. This involves the task of investigating the GDW operating conditions under which the capacity and the power consumption of the vacuum pumps can be reduced without detriment to the parameters of the extracted electron beam, i.e., the task of improving the GDW efficiency. We provide here the experimental data obtained in testing a gas-discharge electron gun with a GDW [5], which indicate that the GDW efficiency can be improved by using the barrier layer effect arising in interaction between a gas jet and the GDW elements.

2. The schematic of the experimental device is shown in Fig. 1. The gas-discharge electron gun 1, which forms a unit with the GDW 2, is placed in the operating chamber 3. The GDW consists of two parts, 4 and 5, which are mounted in water-cooled holders coaxially with the electron gun. The GDW elements can have different shapes (plane, cone, funnel, or some combination of these shapes). The shape of the elements is chosen with a view to ensuring the maximum pressure drop at the GDW (estimated with respect to the ratio of the pressure in the chamber to the pressure in the gun) and a minimum spacing between the elements. The elements can be replaced or moved with respect to each other without disturbing the coaxiality or hermeticity of the holder sealing to a distance from 0 to 30 mm. The elements have coaxial channels with a length of 1 mm and diameters d_2 and $d = 0.6\text{–}1.5$ mm. The gas between the elements is pumped out by means of a mechanical vacuum pump, 6 (VN-7), through a choke, 7, which ensures discrete variation of the effective gas pumping rates: $S_{-} = 6$; 12; 19; 40 liters/sec.

By varying the pumping rate, one can vary over a wide range the pressure drop in the gas flow, determined with respect to the ratio of the chamber pressure p_c to the pressure p_1 in the casing 2 (p_c/p_1). This makes it possible to vary the gasdynamic and the geometric parameters of the jet interacting with element 4 of the GDW.

The electron gun volume is evacuated by means of mechanical pump 9 (VN-1MG). The pressure within the casing (the first GDW stage) is measured by means of vacuum gauge 8 (VSB-1), the pressure p_2 within the electron gun volume (second stage of the GDW) is measured by means of thermocouple gauge 10 (PMT-2), and the pressure in the operating chamber is measured by means of a strain pressure gauge 11. A window covered with lead glass is provided in the casing wall, which makes it possible to observe visually the pattern of gas flow between the GDW elements. Visualization of the gas flow is effected via glow-discharge [6], produced by electrode 12, which is introduced with hermetic sealing between the elements, with a voltage of 300-600 V supplied to the electrode from a UIP-1 universal supply source.

3. A series of experiments were performed in order to determine the possibility of ensuring a maximum gas pressure in the chamber within the operating pressure range of 2-10 Pa in the gun with a minimum spacing between the GDW elements for the purpose of minimizing the

---

Tomsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 2, pp. 3-6, March-April, 1985. Original article submitted January 9, 1984.

0021-8944/85/2602-0151$09.50

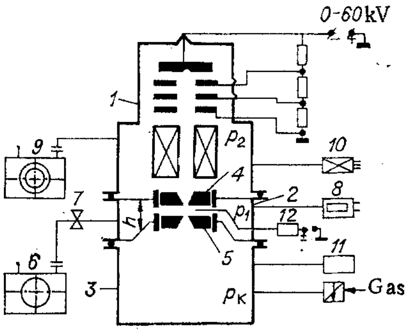

Fig. 1

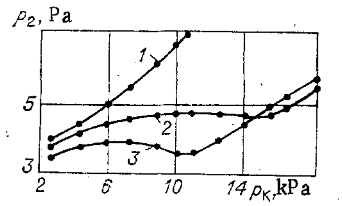

Fig. 2

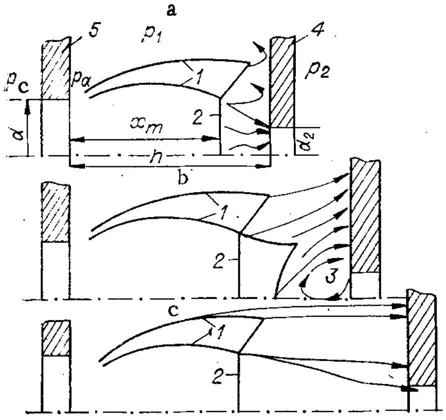

Fig. 3

electron beam loss on the elements in extracting the beam. Figure 2 shows the pressure in the gun as a function of the chamber pressure for different spacings h between flat GDW elements. The curves were plotted for the following conditions: $d = d_2 = 0.8$ mm, $S_- = 12$ liters/sec; the curves pertain to the following h values: 1) h = 4; 2) 8; 3) 6 mm. The behavior of the curves indicates that, for small values of h (curve 1), the pressure in the gun increases almost linearly with the chamber pressure. This is described qualitatively by the well-known equation of vacuum technology, which relates the gas pressure p to the gas flow Q and the gas pumping rate S:

$$p = Q/S. \tag{3.1}$$

As the spacing between the GDW elements increases (Figs. 2 and 3), the behavior of the curves changes. At a certain pressure in the chamber (6-16 kPa), the pressure in the gun no longer depends on the chamber pressure or even displays an inverse relationship (curve 3) ("shelf effect"). This phenomenon, which, at first glance, seems to contradict relationship (3.1), is interesting and useful with regard to the possibility of increasing the pressure drop at the GDW, i.e., increasing its efficiency.

4. It is advisable to discuss the results obtained while also considering the gas flow structure in the GDW. An idea of the flow structure was obtained as a result of visualizing the flow by means of glow-discharge, struck in the space between the GDW elements. The character of the gas flow and the flow structure in this space coincide qualitatively with the characteristics of outflow of a gas jet and its interaction with barriers [7-10]. For a low pressure in the chamber and between the elements ($p_c < 6$ kPa, $p_1 < 15$ Pa; $p_c/p_1 \approx 500$), the gas luminescence in glow-discharge occurs in the form of a luminescent ball. This indicates that the gas outflow into the space between the diaphragms occurs with severe underexpansion of the jet, which is characterized by radial gas outflow in all directions from the operning d. Therefore, a pressure increase in the gun is observed over the initial segment of the chamber pressure rise for any spacing between the diaphragms, i.e., relationship (3.1) holds for p_c/p_1 ratios of up to $p_c/p_1 = 80$-100. With a reduction in the p_c/p_1 ratio between the GDW elements, a barrel-shaped flow is formed with sagging 1 and central 2 (Fig. 3) pressure jumps ahead of diaphragm 4, corresponding to the outflow of an underexpanded jet into a vacuum.

Figure 3 shows modes of interaction between a gas jet flowing out of the opening of GDW element 5 with a barrier in the form of the GDW element 4 for the case of simple flat elements with different spacings between them.

For a small ($h < 2d$) spacing between the GDW elements (Fig. 3a), a considerable part of the flow is intercepted by the opening in diaphragm 4, and it thus enters the gun volume. Conditions for freer jet expansion are created with larger spacings. The gas jet, which has an annular cross section, reaches the element 4. The outer part of the annular gas layer spreads over element 4 in the direction away from the jet axis and is pumped out by pump 6. The inner part of the jet flows toward its axis in the direction of the opening d_2 for beam extraction and then turns to meet the main flow, thus forming a circulation vortex zone 3 (Fig. 3b). We thus observe the formation of circulation flow 3, which exerts ejecting action at the opening d_2 of diaphragm 4 and produces a locking effect, as it were, for the axial flow in the direction of the opening d_2 that communicates with the electron gun volume. The pressure in the gun does not increase (see Fig. 2, curve 2), and it even decreases (see Fig. 2, curve 3), as the chamber pressure rises. The "shelf effect" takes place. For flat GDW elements, its origin corresponds to the condition

$$X_m > h > 0.5X_m, \qquad (4.1)$$

where X_m is the distance to the Mach disk [7]: $X_m = 0.7d\sqrt{kp_a/p_1}$; k is the adiabatic curve exponent for the gas, p_a is the pressure at the cutoff of opening d [11]:

$$p_a = p_k\left(1 - \frac{k-1}{k+1}\lambda_a^2\right)^{k/(k-1)}, \qquad (4.2)$$

and λ_a is the flow velocity coefficient at the cutoff of opening d ($\lambda_a = 1$ for a cylindrical opening, $k = 1.4$ for air, and (4.2) then becomes $p_a = 0.528\ p_c$).

The condition (4.1) is explained qualitatively in [10], where, in interaction between a gas and a flat barrier, a pressure maximum was always observed at the barrier center for $h < 0.5\ X_m$.

For flat GDW elements, with air used as the operating gas, the maximum pressure drop (p_c/p_2) was achieved for $h/d = 9$-11. For $p_c/p_1 < 80$, the spacing corresponding to the maximum pressure drop (p_c/p_2) obeys the law $h = 2X_m$. As the spacing between the GDW elements increases (see Fig. 3c), diaphragm 4 leaves the initial jet section and goes out to the main section, which is characterized by the maximum gas transfer along the jet axis. Therefore, with a further increase in the spacing, the pressure in the gun increases, while the dependence of the gun pressure on the chamber pressure becomes increasingly linear and similar to curve 1 (see Fig. 2), i.e., the " shelf effect" vanishes.

The character of interaction between the flow and element 4 with pressure variation in the chamber is similar to the pattern observed in varying the spacing.

A reduction of the pressure ratio in the gas flow (p_c/p_1) is accompanied by a decrease in the distance X_m and the transverse dimensions of the jet, so that the transverse cross section of the jet diminishes with a reduction in p_c/p_1, which reduces the dimensions of the circulation zone. The ratio of the ejected gas discharge to the ejecting gas discharge (the ejection factor) is thereby reduced, which leads, as follows from ejector theory [11], to a lowering of the maximum ejection pressure at the opening d_2 of diaphragm 4. The pressure in the gun then diminishes (see Fig. 2, curve 3), in spite of the pressure increase in the chamber and between the diaphragms outside the jet. However, with a further reduction in p_c/p_1, the diminution of the jet dimensions causes the peripheral flow to be directed to the opening for beam extraction, and the pressure in the gun correspondingly increases.

Thus, independence of the gun pressure of the chamber pressure ("shelf effect") can be realized by a suitable choice of the geometry of the GDW elements, their mutual positioning, and operating conditions of the device as a whole. Using a GDW with flat elements, openings for beam extraction with $d = d_2 = 0.8$ mm, a spacing of $h = 8$ mm between them, and GDW evacuation by means of only two separate VN-1 MG pumps, we succeeded in raising the chamber pressure from 13.3 to 40 kPa and maintaining the gun pressure at 5 Pa.

The above features of interaction between a gas jet and a barrier indicate that, in many cases, not only the pump efficiency, but also the shape and the mutual arrangement of GDW elements, constitute the decisive factors for ensuring the pressure drop, while the possibility of improving the GDW efficiency depends largely on considering the jet character of the gas flow between GDW elements.

The authors are grateful to A. K. Rebrov and P. A. Skorovodko for useful and stimulating discussions.

LITERATURE CITED

1. G. I. Levin, "Electron-beam welding in an inert gas atmosphere," Svarochn. Proizvod., No. 7 (1971).
2. Yu. I. Bychkov, Yu. D. Korolev, et al., "Excitation of laser media by means of an electron beam, introduced through a gas-dynamic window," Izv. Akad. Nauk SSR, Ser. Fiz., 43, No. 2 (1979).
3. S. S. Kutateladze and A. K. Pebrov (eds.), Diagnostics of Rarified Gas Flows [in Russian], Nauka, Novosibirsk (1979).
4. V. M. Ievlev, and A. S. Koroteev, "Extraction with conveyance to the atmosphere and investigation of stationary high-power electron beams," Izv. Akad. Nauk SSSR, Energ. Transp., No. 3, (1981).
5. V. D. Gitt, P. I. Ryl'tsev, et al., "Gas-discharge electron gun with beam conveyance into a gas under medium pressure," Prib. Tekh. Eksp., No. 4 (1981).
6. S. A. Sankovenko, "Experimental methods of investigating the flow structure and relaxation processes in supersonic gas jets," in: Sixth All-Union Conference on Rarified Gas Dynamics, Abstracts of Reports [in Russian], Institute of Technical Physics, Siberian Branch of the Academy of Sciences of the USSR (ITF SO AN SSSR) [in Russian], (1979).
7. N. I. Kislyakov, A. K. Rebrov, and R. G. Sharafutdinov, "Structure of low-density, high-pressure jets beyond a supersonic nozzle," Zh. Prikl. Mekh. Tekh. Fiz., No. 2 (1975).
8. I. P. Ginzburg, B. G. Semiletenko, and V. N. Uskov, "Experimental investigation of the interaction between an underexpanded jet and a flat barrier perpendicular to the jet axis," in: Gas Dynamics and Heat Exchange [in Russian], Vol. 3, Leningrad State University (LGU),
9. O. I. Gubanova, V. V. Lunev, and L. N. Plastinina, "Central disruption zone in interaction between a supersonic underexpanded jet and a barrier," Izv. Akad. Nauk SSSR, Mekh. Zidk. Gaza, No. 2 (1971).
10. M. M. Golomazov, Yu. M. Davydov, et al., "Investigation of flow fields in the region of interaction between a supersonic underexpanded jet and a barrier," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 3 (1982).
11. G. N. Abramovich, Applied Gas Dynamics [in Russian], Nauka, Moscow (1976).