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Gas – discharge electron sources with gas- dynamic beam output windows

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Abstract. The extraction of focused electron beams via the system of funnels and outlets is discussed. The increase of efficiency is achieved by the use of gas-discharge electron sources, complication of a funnel shape and consideration of a beam effect on pressure differential.

1. The present state of the problem

Electron beams, injected into gas, can find wide application in material machining, metallurgy, quantum electronics and medicine.

The devices with beams removal usually consist of an electron source and an output window that separates its vacuum volume from a chamber, filled with a gas. The window for extraction of high-energy beams (above 100 KeV) can be made of a metal or polymer film, transparent for electrons, but opaque to gases. For extraction of low-energy continuous focused electron beams the gas-dynamic windows, consisting of supersonic gas jets, metal vapor jets and liquid jets can be used. Besides, jet gates for extraction of focused beams some systems of aligned diaphragms can be used with differential gas pumping between them [1-13]. The pressure differential, obtained with such means, increases with a number of stages and pumping capacity, but drops with the increase of output hole dimensions. Gas-dynamic windows parameters can be improved by a better design of gas-dynamic windows itself and also of pumping means. The decrease of an incoming gas can be achieved by overlapping of holes in the case of beams absence, e.g. using a rotating cylinder with a channel for beams extraction, or with a disk with holes at its edge for the same purpose. With advances in vacuum techniques instead of mechanical pumping means cryogenic and ejector ones are used currently.

Now existing means for extraction of stationary beams through the system of diaphragms allow to extract beams into atmosphere from electron sources with a thermal cathode, operating at pressures of the order 10^{-3} Pa, using 5-6 pumping stages, through holes with the diameter 1-10 mm with power consumption about 5-7 KW per 1 mm of the hole area and current losses up to 75%.

Despite growing interest to application of continuous beams their application is retarded by a number of problems, evolving in the process of electron sources operation with gas-dynamic windows. The main of them is contradiction between hole dimensions for beams extraction and capacity of pumping means to maintain vacuum for electron generation.

In most cases a beam is extracted with probabilistic forecasting as to a pressure differential and removed power. However, in some cases a form and mutual arrangement of gas-dynamic windows elements together with the passing beam modes can define a pressure differential and beam losses, but not capacity of pumping means. One of the reasons of probabilistic efficiency of beams extraction is the fact that well-known calculation methods, based on relationships of vacuum techniques, can not reveal the conditions of efficiency increase, but only establish tentative correlation between the hole diameter and necessary gas pumping rate.

2. Problem solution

The increase of beams extraction efficiency is related to solution of a number of problems that can be subdivided according to the following directions: an electron source, pressure differential system, electro physical events, current passage, correlation.

3. Electron source

The employment of gas-discharge electron sources, operating in mud vacuum, is rather promising. The advances in electron - beam and plasma technologies of electron guns, based on Penning gas discharge and high-voltage glow discharge, operating in forvacuum under conditions of lesser requirements to gas-dynamic windows parameters which allows to use only mechanical pumps and to utilize gas-dynamic effects to increase a pressure differential. The development of multi-channel electron guns as electron sources that can generate electron beams at pressures of 80 Pa and more [14] was great achievement in this field. On figure 1 the scheme of electron source on the base of high-voltage smoulder discharge with gas-dynamic window is described.

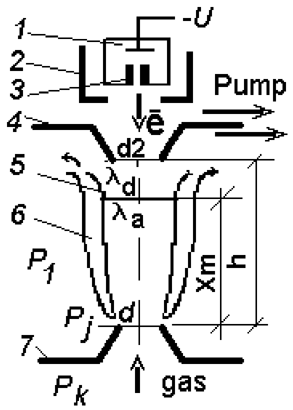

Figure 1. The scheme of electron source on the base of high-voltage smoulder discharge with gas-dynamic window. *1* – Cathode, *2* – anode, *3* – magnetic lens, *4*, *7* – gas-dynamic window, *5* – Mach disk, *6* – jumps of pressure.

The source consists of a cold aluminum cathode *1* and anodes *2*, between which the high-resistance resistor R is included. At pressure in the source of 1-10 Pa the negative potential (up to 100 kW) is given on a cathode. Between cathode and anode the high-voltage smoulder discharge is lighted. An ion from plasma of the discharge directs on cathode. From cathode are dislodged electrons under action of ion-electronic emission. The electron beam is focused by the magnetic lens *3* in the holes of elements *4,7* of gas-dynamic window and are removed in the camera. Gas flow from the working camera is formed in a kind of supersonic jet with jumps of pressure *5* and *6*. Transverse jump of pressure *5* means a Mach disk. Distance X_m up to Mach disk is described by following [15]:

$$X_m = 0{,}7d\sqrt{kP_J / P_1} \qquad (1)$$

Where k - is a factor of gas adiabatic, P_j - is pressure on the element cut, P_1 - is pressure between elements.

4. Pressure differential system

The most promising means for provision of a pressure differential is the system of aligned diaphragms of different shapes. There is an optimum distance which corresponds to the maximum pressure differential. To optimize the element shapes and the analysis of gas- dynamic effects a jet supersonic model of a gas flow has proved its efficiency. At the pressure differential above two orders at a hole an element shape does not effect pressure in an electron source, which is related to compliance of the principle of independence of flow parameters on a body shape. For accounts on figure 2 the experimental dependencies of optimum distance between elements, at which difference of pressure is maximum for geometric sharp (curve 2) and flat (curve 1) elements are submitted.

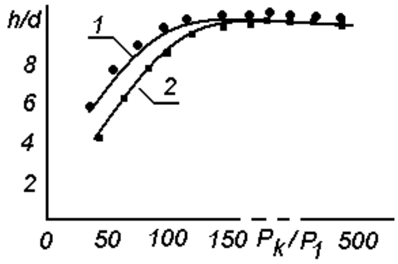

Figure 2. The experimental dependencies of optimum distance between elements, at which difference of pressure. 1 – flat elements, 2 – sharp elements

Initial area of curves coincided with known ratio for Mach disk. Stabilization and some reduction of optimum distance with increase of difference of pressure is connected with fact that at the difference of more than two orders (M>3) the principle of flow independence from the body form is executed. In this case under h/d>10 the calculation of differential pump out system can be carried out on ratios of vacuum technique. However, the employment of gas-dynamic effects under conditions of low pressure becomes problematic one due to gas rarefaction; pressure decrease causes the decrease of gas pumping means efficiency. Energy input for gas pumping out is limited by dimensions of pumping means and by capacity of vacuum communications; the complexity of element shapes is also limited by the pressure recovery limit in a gas flow by *(k+1)/(k-1)* times.

5. Electro physical effects

To provide a pressure differential it is useful to apply the pumping effect, produced by an extracted beam, or by a discharge, ignited between elements [16-21]. Gas, flowing into the vacuum, is accelerated into the region of supersonic velocities, and expands in the form of a hollow jet with formation of the pressure compacting zone (Mach disk) in front of the output elements. Following the Mach disk the flow is decelerated and its pressure increases.

However, an extracted beam and a discharge in some cases can impair a produced pressure differential. The influence of an extracted beam on a pressure differential can be analyzed, using the scheme of a gas flow and changes of its parameters at a pressure differential (figure 3).

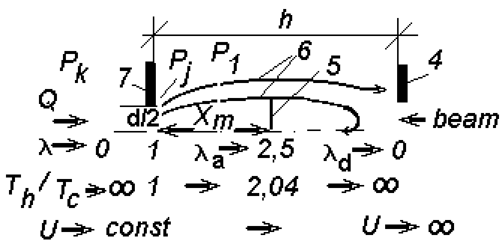

Figure 3. The scheme of a gas flow and changes of its parameters at a pressure differential. *4*, *7* – gas-dynamic window, *5* – Mach disk, *6* – jumps of pressure.

The scheme of gas parameters changing is based on the temperature dependence of the holes capacity U and also on a thermal model of beam interactions with a gas, according to which the greater is a coefficient of a flow velocity the lesser are its ability to be heated and pressing pressure in a gas flow. Gas temperature change is related to the change of the flow velocity coefficient λ with relation:

$$T_h / T_c = (1+\lambda_c{}^2)/4\lambda^2{}_c \tag{2}$$

The indices "h" and "c" correspond to hot and cold gases. It is evident that the lesser is a gas velocity the greater is its heating. The gas flow rate change Q in the course of heating can be defined by the expression:

$$Q_c / Q_h = [2T_h / T_c - 1]^{0,5} \tag{3}$$

In the inter element space the velocity coefficient λ can take limiting values from 1 to 2.5. Correspondingly limiting temperature changes can take values from 1 to 2,04. Thus, a limiting gas flow drop due to gas heating by a beam cannot exceed 1,75 for the air.

Table 1 gives the values of the total pressure change function $f(\lambda)$ for gas heating in subsonic and supersonic jet regions in an output facility, taken from paper [15]:

$$f(\lambda) = (\lambda^2 + 1)[1 - (k-1)/(k+1)\lambda^2]^{1/(k-1)} \tag{4}$$

Table 1. Some parameters of a gas flow

λ	0	0,528	1	2	2,5
$f(\lambda)$	1	1,1	1,2	0,32	0

The table shows that the value of the total pressure change function f in a supersonic region decreases by more than 2 orders. In a subsonic jet region the total pressure does not almost change during gas heating. In an operating chamber a flow is motionless $\lambda \to 0$; $T_h/T_c \to \infty$. In the region of a beam input into a chamber $\lambda \to 1$; $T_h/T_c \to 1$; consequently the hole capacity remains constant.

$$U \sim (T/M)^{0,5} \tag{5}$$

Where T is temperature, M is gas molecular weight. The gas flow rate into the system of pressure differential near a beam decreases at the expense of the gas density decrease, applied to the chamber out of the beam output region.

The flow in an inter element space up to Mach disk is accelerated from $\lambda = 1$ to λ_a. In a supersonic region and decelerated from $\lambda_d = 1/\lambda_a$; to $\lambda = 1$ in a subsonic region after a shock wave. Without a beam effect the gas temperature decreases with a velocity increase, but being effected by a beam it increases. At maximum flow (air) velocity we have:

$$M \to \infty, \lambda \to 2{,}5;\ T_h / T_c \to 2{,}04;\ \delta = (1) / f(\lambda_a)$$

Approaching the element of the second pumping stage in a subsonic region the jet flow is decelerated. $\lambda_d \to 0$; $T_h/T_c \to \infty$ which increases the capacity ($U \to \infty$).

The coefficient of the total pressure change is expressed by:

$$\begin{aligned} \delta &= [f(0)/f(1)][f(1)/f(\lambda_a)][f(\lambda_d)/f(1)] \approx \\ & f(\lambda_d)/f(\lambda_a) \approx f(0{,}46)/f(\lambda_a) \end{aligned} \tag{6}$$

So the total pressure change during beam passage (6) is defined by relationship of the total pressure change functions behind a shock wave and in front of it. Deterioration of the pressure differential, affected by a beam, can be explained by the fact, that at a small interval between elements the flow principally consists of a subsonic region with great gas heating and correspondingly great hole capacity.

6. Current passage

By contrast to traditional notions about current passage value, determined by relationships between diameter of a beam and an output hole, current passage can increase during formation of a concave plasma boundary in the neighborhood of elements under specific compromise between a pressure differential and an element shape. In the region of unsteady interactions of a gas flow with elements of extracting means the current passage is of unsteady character. When approaching the channels of extracting means the current passage is of unsteady character.

During discharge generation in gas-dynamic windows a part of a transported beam can be screened. The current passage from high current electron sources is defined by a geometrical form of a plasma flow as far as an extraction system.

7. Correlation

An electron source with a beam extraction means is a unified complex, in which both a volt-ampere characteristic and also the increase and decrease of a pressure and current losses depend on beam parameters, mutual arrangement and a shape of extracting elements.

The increase of a source operating pressure can be achieved at the expense of harder discharge ignition and by leak- in of light gases (He) into a source. The employment of a cold cathode with a central insertion made of a material with a high coefficient on ion-electron emission (LaB_6) in combination with an optimal focusing optical system enable to increase beams brightness and to decrease its losses during extraction. The current passage at a pressure differential can be higher, compared with the case without a differential, which is related to the effect of ion focusing in forming of a plasma boundary in the region of extracting means elements. In contrast to traditional notions a gas-dynamic windows is a multi-functional means and can be adjusted either to a maximum pressure differential (by provision of ejector events in the neighborhood of elements) or to a maximum current passage (with hole dimensions, not exceeding internal dimensions of a jet) or to generation of pressure oscillations or the fulfillment of the pressure stabilization function (in the range of Reynolds numbers 150-200). In fabrication of elements with dimensions not greater than internal dimensions of a jet cavity a flat shape is flowed around in a mode of a sharp body. Due to this the notion of the element shape has not geometrical, but a parametric sense. With the pressure drop the priority in provision of a pressure differential passes to the systems with a discharge between gas-dynamic windows elements.

Results

A new gas-dynamic method for calculation of systems for beams transfer was developed that allows to optimize calculations of required parameters together with new multi-channel and multi-functional gas-discharge electron sources at the operating pressure up to 80 Pa and higher, the power consumption of pumping means was reduced in the source of beams output into atmosphere from 10 to 1.5 KW/mm per 1 mm of a hole area at the distance between diaphragms from 2 to 5 diameters of output holes.

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