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High-vacuum Pump of Orbitron Type: Electrophysical Principles of Work and Design Features

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The article presents the results of studies of the operation of an orbitron getter-ion vacuum pump (OGIP) with nitrogen cryopanel. The paper presents the calculated average values of specific pumping speeds of various gases with a titanium film. A special feature of the OGIP is that the electrons therein emitted by the thermal cathode are used for both heating and sublimation of Ti, and for the ionization of gas molecules. The active gases are pumped out due to the chemisorption of the continuously renewed titanium film, the inert gases as a result of the ionization of their atoms by electrons moving in the cavity of the pump, the further accelerated movement of the formed ions to the wall of the pump casing by implanting them into the titanium film and "immurement" Ti deposited in it. The same accelerated electrons ionize a certain part of the molecules of active gases and heavy hydrocarbons, which are also sorbed by the titanium film. The article also describes the design features of the OGIP and its modes of operation. With the help of the MX7304A mass spectrometer, the composition of the residual atmosphere of the vacuum chamber was studied when it was pumped out to an ultrahigh vacuum, depending on the operating modes of OGIP. It was found that the main feature of the mass spectra of the residual atmosphere of the vacuum chamber when it is pumped out by OGIP is the complete absence of peaks with $M > 44$ amu in the mass spectra (molecules of heavy hydrocarbons). The main component of the residual atmosphere during water cooling of OGIP is methane CH_4, the amount of which determines the ultimate vacuum in the chamber. When using nitrogen cryopanel, the main component of the residual atmosphere is H_2O water vapor. The conclusion is drawn that the designed OGIP with nitrogen cryopanel is an effective pumping out tool for creating an ultrahigh oil-free vacuum in metal vacuum units that are fully heated.

Keywords: Ultrahigh oil-free vacuum, Orbitron getter-ion vacuum pump, Residual atmosphere mass spectrum.

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1. INTRODUCTION

New requirements for the quality of the vacuum environment, first of all to the purity and degree of vacuum, that were advanced to vacuum science and technology at the end of the 20th century, and which are based on the modern development of electronics, spintronics, nanotechnologies, technologies for the extraction of substances, etc., predetermine both the creation of fundamentally new means of obtaining vacuum and its diagnostics, as well as improving existing ones [1, 2].

In this regard, it should be noted that, despite some progress in the development of vacuum technology over the past 25-30 years, which is mainly related to the miniaturization of various electronic devices used in vacuum technology and the widespread use of computer technology, no "breakthrough" developments in the progress of vacuum technology did not occur. If we talk about vacuum pumps as a means for obtaining and maintaining ultra-high (less than 10^{-7} Pa (10^{-9} Torr)) vacuum, then of the 5 main types of vacuum pumps inherited from vacuum technology of the second half of the 20th century (diffusion, turbomolecular, ionic magnetic-discharge, cryogenic and electrophysical), only the last two satisfy these requirements [3].

Cryogenic ultrahigh vacuum pumps are still the leaders among modern vacuum pumps both in terms of vacuum depth (less than 10^{-10}-10^{-12} Pa (10^{-12}-10^{-14} Torr)) and in its quality (total absence of hydrocarbons). However, the complexity of obtaining, preserving and high cost of the main refrigerant for these pumps – liquid helium, allows to operate cryogenic pumps only in large research centers.

Electrophysical (getter-ion) ultrahigh vacuum pumps are structurally simple (which makes it possible to manufacture and operate them in small research laboratories) and have quite acceptable characteristics – a limiting vacuum of 10^{-10} Pa (10^{-12} Torr) in the complete absence of heavy hydrocarbons [3, 4].

This paper presents the results of research work of one of the types of electrophysical pumps – getter-ion vacuum orbitron type pump.

2. MAIN PART

2.1 Principles of Ion-heater Vacuum Pumps

The ion-getter pump is a combined pump that combines evaporative and ion pumps. Evaporation vacuum pumps are pumps whose failure action is based on the use of the getter properties of a film obtained by condensation of thermally evaporated atoms of active metals. In them, the film of active metal covers a specially designed for it a large surface (the inner surface of the pump housing or special screens) and continuously or periodically restored during the operation of the pump. In addition, from time to time, the old film can be mechanically removed from these surfaces, clearing them

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to deposit a new film. Today, there are several dozens of their modifications, which differ the starting active metals and the methods of their evaporation.

Chemically active metals such as Ba, Ti, Zr, Ta, Mo, Mg, Hf, Er, Y can be used as the starting getter metal. In most modern evaporation pumps, the starting metal is titanium as the cheapest. Titanium forms strong non-volatile compounds and solid solutions with atoms of almost all gases in vacuum systems, except inert gases.

Let us consider in more detail the mechanism of gas evacuation by a film of active metal deposited on the surface of the wall of the pump housing. A gas molecule that (due to chaotic motion) has hit the surface of the pump wall, for some time is in the adsorbed state. The adsorption time according to the Frenkel formula is

$$\tau = \tau_0 e^{\frac{Q_a}{RT}}, \quad (1)$$

where τ_0 is a certain constant, the same for all gases and equal to ~ 10^{-13} s; Q_a is the heat of adsorption (the binding energy of the gas molecule with the surface); R is the universal gas constant; T is the absolute surface temperature.

For the main components of air, the heat of physical adsorption is set $Q_a \approx 20$ kJ/mol. In the case of the formula (1), for the room temperature of the surface for the adsorbed gas molecules it is close to 10^{-10} s, and for the surface, whose temperature is equal to the temperature of liquid nitrogen $T = 77$ K, it is close to 1 s.

For water vapor and vacuum oil vapor molecules, the heat of physical sorption is $Q_a \approx 80$ kJ/mol, which corresponds to the adsorption time $\tau \approx 100$ s at $T = 293$ K and $\tau = 10^{43}$ s at $T = 77$ K. For helium $Q_a = 2$ kJ/mol, therefore, the adsorption time of its atoms even at $T = 77$ K is close to the minimum ($\tau = 10^{-13}$ s).

If the surface on which the gas molecule fell is made of a chemically active metal Me (metals mentioned earlier), a chemical reaction can occur between physically adsorbed gas molecules and surface atoms with the formation of chemical compounds on the surface (hydrides MeH, oxides MeO, nitrides MeN, etc.). As a result, gas molecules are reliably bound by the surface layer of the metal (chemisorption).

If we use equation (1) to describe such sorption, now the magnitude of the heat of sorption (the magnitude of the binding energy of the gas molecule with the surface) will be equal to the heat of chemisorption

$$Q_a = Q_c, \quad (2)$$

which is much larger than in the case of physical sorption. For example, the value of Q_c for oxygen chemisorbed on the surface of titanium is about 10^3 kJ/mol, whereas with the physical adsorption of oxygen on the metal surface, the value of the binding energy Q_a = 12-17 kJ/mol. Therefore, the adsorption time of the oxygen molecule on the titanium surface during chemisorption is almost infinitely large even at room surface temperature. In other words, the probability of desorption of the oxygen molecule chemisorbed on the titanium surface is an extremely small value that can be considered equal to zero.

It should be noted that a low surface temperature (as in the case of physical adsorption) is not mandatory for increasing the "settle time" of the molecule during chemisorption. On the contrary, depending on the gas-metal pair, the chemisorption processes occur more actively at room and higher temperatures. At low temperatures, chemical reactions slow down or do not occur at all. Thus, the efficiency of chemocoupling (adsorption time) of gas molecules by the surface at low temperatures decreases.

The specific values of the binding energy (heat of sorption) Q_c depend on the gas-metal pair and the temperature of the metal surface. Table 1 shows the values of the heat of sorption of different gases on titanium films at room temperature.

Table 1 shows that gases, such as CO, N_2, O_2, CO_2, (active gases) are chemisorbed on the surface of the titanium film, and inert gases and hydrogen are on the surface of the film in a physically adsorbed state. Therefore, the active gases will be well absorbed by the titanium film (their desorption practically does not occur), and the inert gases are practically not retained by the film and are easily desorbed from its surface.

Table 1 – The value of the heat of sorption (Q) of gases by a titanium film [3]

Gas	H_2	CO	N_2	O_2	CO_2	Xe	Kr	Ar
Q, kJ/mol	19.3	419	356	813	461	33.5	16.8	8.38

To characterize the evacuation properties of pumps with a film of active metal, it is necessary to take into account not only the value of the heat of sorption, but also the so-called "coefficient of sticking" of molecules of one or another gas to the film. The coefficient of sticking understand the value equal to

$$\beta = \frac{n_1}{n_0}, \quad (3)$$

where n_0 is the number of gas molecules that fell per unit surface of the film per unit of time; n_1 is the number of gas molecules that were connected by a unit of the film surface per unit of time.

It is absolutely clear that in the case of an ideal sorbing surface (when all gas molecules that fell on the surface are bound by it) $\beta = 1$. For real films, $\beta < 1$. The value of the sticking coefficient cannot be calculated theoretically (except for the ideal sorbing surface) due to the complexity and lack of knowledge until the end of the processes that occur on the surface of the active film during its bombardment with gas molecules. The value of β depends on many factors (film history and its structure, temperature and method of spraying, gas composition, etc.) and is determined experimentally. Table 2 summarizes the sticking coefficients β of different gases for freshly condensed titanium film and calculated according to these data, the specific gas pumping out speed of such a film. The specific pumping out speed is calculated by the formula

$$s = \beta s_0, \quad (4)$$

where β is the sticking coefficient; s_0 is the specific pumping out speed of the ideal sorbing surface

$$s_0 = \sqrt{\frac{R}{2\pi}} \cdot \sqrt{\frac{T}{\mu}} = 3,64\sqrt{\frac{T}{\mu}}, \quad (5)$$

where T is the absolute temperature of the gas; μ is the molar mass of gas in atomic mass unit.

From Table 1 it follows that for getter pumps with titanium film, there is a significant pumping out selectivity – inert gases (as expected) are not pumped out at all by such pumps. For water vapor, the surface of the titanium film is almost ideal sorbing surface ($\beta = 1$), for other gases, the sticking coefficient β ranges from 0.001 (methane CH_4) to 0.92 (carbon dioxide CO_2).

Table 2 – Average values of sticking coefficients β and specific pumping out speeds of different gases with a titanium film (gas temperature $T = 293$ K) [3]

Gas	μ, amu	Ideal sorbing surface		Titanium film			
				$T = 293$ K		$T = 77$ K	
		β_0	s_0, l/s·sm²	β	s, l/s·sm²	β	s, l/s·sm²
H_2	2	1.0	44.2	0.11	4.7	0.22	10.0
N_2	28	1.0	11.8	0.4	4.8	0.8	9.2
CO	28	1.0	11.8	0.66	7.8	0.85	10.0
O_2	32	1.0	11.0	0.91	10.0	0.66	7.3
CO_2	44	1.0	9.4	0.5	4.7	0.92	8.6
H_2O	18	1.0	14.7	1.0	14.7	1.0	14.7
CH_4	16	1.0	15.6	0.001	0.01	0.01	1.0
He	4	1.0	31.1	0	0	0	0
Ne	20	1.0	13.9	0	0	0	0
Ar	40	1.0	9.8	0.001	0.01	0	0
Kr	83	1.0	6.8	0	0	0	0
Xe	130	1.0	5.4	0	0	0	0

It was discovered in 1962 that the absorbing effect of a titanium film is significantly improved if it condenses not on the surface at room temperature, but on a surface that is cooled with liquid nitrogen ($T = 77$ K). Thus, for most gases at the nitrogen temperature of the titanium film, an increase in the value of β is almost twofold. The exception is oxygen, for which at room temperature the titanium film is an almost ideal sorbing surface ($\beta = 0.91$), and at $T = 77$ K the sticking coefficient decreases to value $\beta = 0.66$. Obviously, this is due to the slowing down of the titanium oxidation reaction at low temperatures. The film of pure Ti does not absorb inert gases at $T = 77$ K, but it was also found that the film of TiO_2 absorbs argon at $T = 77$ K with a sticking coefficient $\beta = 0.17$ (see [3]).

It was established experimentally that the improvement in the pumping out of gases by the titanium film, which was obtained at a temperature $T = 77$ K, is due to its structure. It turns out that the sticking coefficient of gas molecules β is the larger, the finer the crystalline structure (smaller crystallites) of a titanium film (see [5]). Most likely, the reason for this increase in β is the growth of the real surface of the titanium film formed by small crystallites, as compared with the surface of the film consisting of large crystallites. Here we have the same situation as for porous compact getters. From the physics of thin films [5] it is known that the crystalline structure of a condensed metal film will be finer, the lower the temperature of the pad on which it condenses, and at $T = 77$ K the titanium film is nanocrystalline. Confirmation of such a mechanism for increasing the sticking ratio is that a titanium film condensed at a substrate temperature $T = 300$ K, and then cooled to $T = 77$ K, does not have such a high value of β as a titanium film condensed at a substrate temperature $T = 77$ K. The crystalline structure of a film formed at a substrate temperature $T = 300$ K consists of large crystallites, and therefore further cooling of the film to $T = 77$ K does not change their dimensions.

Due to the considerable selectivity of pumping out different gases, the residual atmosphere of titanium sublimation pumps will be enriched with inert gases, methane (CH_4).

The study of the causes of methane appearance in the residual atmosphere of sublimation pumps has been the subject of research for several years (see [5]).

The content of methane in atmospheric air is very small (about $1 \cdot 10^{-5}$ %), and in the residual atmosphere of sublimation titanium pumps methane is its main component, which determines the limiting pressure of these pumps. It was found that methane is synthesized in the pump itself during its operation. As a result of pumping out H_2 by the titanium film on the surface of the titanium film, CH_4 is synthesized as a result of a catalytic reaction

$$2H_2 + C = CH_4,$$

in which titanium acts as a catalyst.

The carbon source for the reaction can be adsorbed by the film before CO and CO_2, as well as free carbon dissolved in the film. The source of hydrogen can be both free hydrogen in the residual atmosphere and hydrogen, which was formed on the surface of the film as a result of sorption of water vapor. Water vapor sorption by a titanium film (as well as compact titanium) occurs very actively (Table 2) and is accompanied by the release of hydrogen (the H_2O molecule decomposes during sorption

$$H_2O \rightarrow H_2 + O$$

and the formed oxygen atom is actively chemisorbed by the surface of the film).

The sticking coefficient for methane, even at a titanium film temperature $T = 77$ K, has a very small value $\beta = 0.01$ (Table 2). A small amount of methane absorbed by the film at $T = 77$ K is completely released when it is heated to $T = 120$-130 K, that is methane absorption is not irreversible.

The data given in Table 2 characterize a freshly condensed titanium film. Like other sorption pumps, a titanium sublimation pump has a specific absorption capacity for a particular gas. The magnitude of the absorption capacity due to the complexity and lack of knowledge until the end of the sublimation phenomena cannot be calculated theoretically and is determined experimentally. It depends on many factors: the thickness, temperature and structure of the film and the degree of coating of the film surface with gas molecules. It is absolutely clear that if all Ti atoms on the film surface chemically have reacted with gas atoms and there is no withdrawal (diffusion) of the latter to the depth (thickness) of the film, then further sorption of gas molecules by such a film will not occur. In other words, in the process of pumping out (with an increase in the degree of coverage of the surface

of the active metal film with gas molecules), the adhesion coefficient of gas molecules β will decrease, and the specific pumping out speed s will decrease accordingly. To restore sorption, the surface of the film should be covered with new layers of titanium atoms.

The peculiarity of the H_2-Ti pair is the highest sorption capacity of titanium for hydrogen as compared to other gases [3]. The magnitude of the sorption capacity of titanium for hydrogen is greater than approximately 500 times the magnitude of the sorption capacity for oxygen, nitrogen and carbon monoxide.

It should also be pointed out that in the case of sorption of a mixture of different gases, competition arises and discrimination in the sorption of different gas molecules. Due to the complexity of researching these processes, data from various researchers are extremely contradictory.

2.2 Getter-ion Pumps of Orbitron Type

In getter-ion pumps, pumping out gas molecules with a titanium film improves due to the ionization of some of them. Historically, the first to be created are getter-ion pumps (pumps of the GIP series), in which the evaporator of titanium and the ionizer of gas molecules operate independently of each other and are not functionally interconnected. In these pumps, the probability of ionization of gas molecules is negligible. Therefore, the rate of pumping of inert gases is insignificant.

This deficiency of GIP is overcome in evaporative getter-ion pumps of the orbitron type (OGIP). For the first time such a pump was proposed by Herb in the 60s of the last century [6]. In OGIP, the same electrons are used both for heating and sublimation of Ti, and for the ionization of gas molecules. The work of OGIP is described in detail in [3].

The active gases are pumped out by the pump due to the chemisorption of the continuously renewed titanium film. Inert gases are pumped out by the pump due to the ionization of their atoms by electrons that move in the cavity of the pump, further accelerated movement of the formed positive ions to the negatively charged wall of the pump casing by implanting them into a titanium film and "immurement" Ti atoms in it. By the same accelerated electrons, a certain part of the molecules of the active gases and the molecules of heavy hydrocarbons are ionized into fragments, which are also sorbed by the titanium film.

Thus, the pumping out mechanism of the orbitron pump combines the chemisorption pumping out mechanism of the titanium sublimation pump and the pumping out mechanism of ion pumps. To calculate the pumping out speed of active gases by an orbitron pump, you can use the data in Table 2.

The speed of the action of orbitron pumps, as well as sublimation titanium pumps, is determined by the value of the surface area of the pump wall covered with a titanium film and the capture coefficient. The ultimate vacuum of orbitron pumps with cooling of the pump casing (titanium film) with running water (room temperature) is 10^{-8}-10^{-9} Pa (10^{-10}-10^{-11} Torr). The use of nitrogen cryopanel ($T = 77$ K), on which a part of Ti atoms is deposited, makes it possible to obtain an ultimate vacuum of the order of 10^{-11} Pa (10^{-13} Torr).

3. EXPERIMENTAL EQUIPMENT

To investigate the operation of the orbitron pump, an ultrahigh vacuum installation UVBL-6 (vacuum oil-free laboratory devise) was created, the schematic diagram of which is shown in Fig. 1.

The preliminary vacuum of $1 \cdot 10^{-2}$ Pa in the vacuum chamber and in the magnetic-discharge NM and orbitron NE pumps is created by three adsorption coal pumps NA_1-NA_3 using valves VR_3-VR_8 with metal sealing cones Du12.

A high vacuum up to 10^{-6} Pa in the vacuum chamber is created using a magnetic-discharge pump, which is connected to the vacuum chamber using a high-vacuum metal valve VR_1, the body of which can be heated up to 300 °C for degassing. The finish ultrahigh vacuum in the vacuum chamber is created with the help of the orbitron pump NE. The pump is connected to the vacuum chamber using a VR_2 valve, the design of which is similar to that of the VR_1 valve. The mass spectra of the residual atmosphere of the vacuum chamber are obtained using a monopole mass spectrometer S type MX7304A.

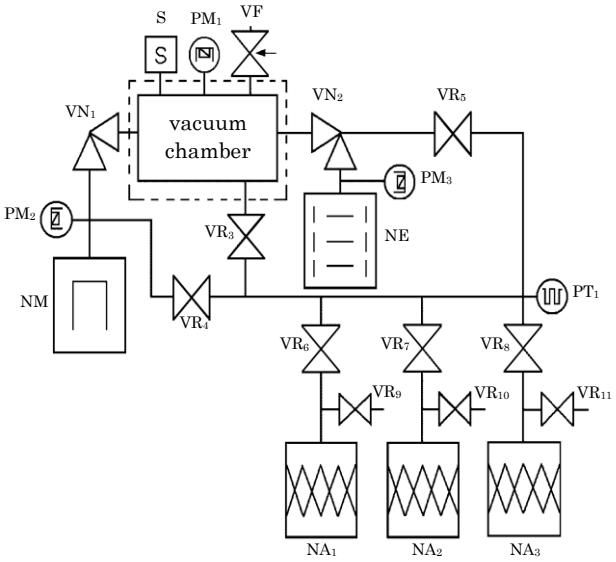

Fig. 1 – Schematic diagram of the ultrahigh-vacuum installation UVBL-6 with magnetic-discharge and orbitron pumps

The main elements of the UVBL-6 vacuum system are the orbitron pump, the magnetic-discharge pump, the system of three adsorption coal pumps for creating a preliminary oil-free vacuum and a cylindrical vacuum chamber with a volume of about 20 liters. All elements of the vacuum system are mounted on a massive base plate. Magnetic-discharge pump NMD-0.16 is mounted under the plate. The UVBL-6 vacuum system also includes piping and valves, which enable independent pumping of any of the system elements (orbitron pump, magnetic-discharge pump, vacuum chamber) to a preliminary vacuum of 10^{-2} Pa by adsorption pumps.

The orbitron pump is connected to the vacuum chamber by a valve with DU-60. The same valve is connected to a vacuum chamber and a magnetic-discharge pump. The orbitron pump housing, magnet-discharge pump housing, high-vacuum valve housings and vacuum

chamber can be heated to 300 °C with electric heaters, and the orbitron pump housing and vacuum chamber can also be cooled with running water (the heaters and water cooling coils are covered with metal covers of the pump housing and chamber).

High vacuum in the vacuum chamber and both pumps is measured using PM_1-PM_3 gauge transducers type PMM-32 with a vacuum gauge of the control panel with the installation. The preliminary vacuum is measured using a PT_1 gauge transducer type PMT-2.

The ultimate vacuum in the vacuum chamber (better than $1{\cdot}10^{-8}$ Pa) is created as a result of its continuous pumping out with degassing heating to 300 °C for 10 hours 15-20 hours after the start of pumping.

3.1 Design Particular Qualities of the Orbitron Pump

The orbitron pump under study (Fig. 2) consists of three main assemblies: a housing (1) with water cooling, a flange with an electrode system (2), and a com partment (3) for a nitrogen cryopanel. The pump is connected to the vacuum system through the nozzle (5), the PMM-32 vacuum gauge transducer is connected to the nozzle (4) to measure the vacuum in the pump.

The anode rod (7) is made of tungsten wire with a diameter of 2 mm; a cylinder (8) made of titanium iodide is fixed to the rod. The filament of the cathode (10) has a diameter of 0.12 mm and is made of a tungsten-rhenium alloy. The pump has two identical cathodes – working and backup. Screen plate (9) with screen tube is made of stainless steel. Elements of the electrode system are assembled on the rods-current leads of the base (11).

The working position of the pump is vertical with a base at the top (as shown in Fig. 2). In the lower part of the pump in a special compartment (3) there is a nitrogen cryopanel (6) formed by the outer surface of the container, where liquid nitrogen is poured. The container is made of thin stainless steel sheet.

The Ti atoms that evaporate from the heated titanium cylinder (8) are deposited both on the side surface of the inner wall of the pump casing (1) (water cooling) and on the surfaces of the container with liquid nitrogen (cooling to $T = 77$ K). Container for liquid nitrogen has an internal diameter slightly larger than the diameter of the pump housing so that titanium film pieces, which can detach from the wall of the pump housing over time, fall on its bottom and stay there at low temperature (this reduces gas emission).

The electronic power supply provides power to the anode and cathode OGIP. Anode voltage can vary in the range of 0-7 kV. Anode current can vary in the range of 0-50 mA. The heating current of the cathode filament varies between 0-3.2 A. The pump housing is grounded.

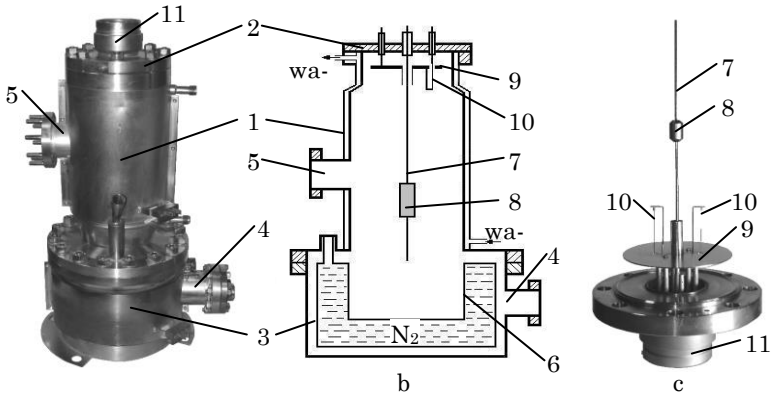

Fig. 2 – Appearance (a), schematic image of the construction (b) and electrode system (c) of the orbitron pump: 1 – housing; 2 – electrode flange; 3 – compartment for nitrogen cryopanel; 4 – nozzle for PMM-32; 5 – connecting nozzle ; 6 – nitrogen cryopanel; 7 – anode; 8 – titanium cylinder; 9 – screen plate; 10 – cathode; 11 – base

The estimated action speed of the pump for air is about 500 l/s in the case of cooling the pump casing with running water and about 600 l/s in the case of using nitrogen cryopanel cooled to $T = 77$ K. The limiting vacuum of the pump when the pump housing is cooled with running water is 10^{-7} Pa, when using nitrogen cryopanel cooled to $T = 77$ K, is not worse than 10^{-10} Pa.

4. DESCRIPTION AND ANALYSIS OF RESULTS

The vacuum parameters of the pump (action speed, ultimate vacuum) are determined by the operating modes of its electrode system. Sublimation of titanium atoms from the surface of a titanium cylinder occurs at a certain electron beam power, which can be changed in three ways: by changing the cathode filament current, by changing the anode voltage and the bias voltage. At low heating currents of the cathode, the number of electrons (the magnitude of the electrical current) is not enough for a noticeable heating of the titanium cylinder. In this mode, the titanium does not evaporate and OGIP works as an ion pump. A similar situation can be created by reducing the anode voltage to $U_A = 1$-2 kV. Thus, the orbitron pump can be easily transferred to the "watchdog" mode of operation, when it is only necessary to maintain a high or ultrahigh vacuum in a recipient with a small amount of gas or gas release.

The power that is released at the anode can be regulated by changing the bias voltage U_b. When this happens, the focusing of the electron beam on the anode changes and the shape of the electron orbits changes. The latter significantly affects the efficiency of ion pumping out.

The pump provides for the possibility of mounting an additional electrode in the form of a liquid cylindrical molybdenum wire grid. The grid is installed near the pump housing and a negative potential is applied to it, which can be adjusted from 0 to 2 kV. The presence of

such a grid makes it possible, by selecting its potential, to improve the pumping out speed of a certain inert gas.

The orbitron pump disconnected and cut off from the vacuum system for a long time maintains a high vacuum, which allows it to be started without the use of preliminary vacuum pumps.

Before discussing the results of mass spectrometric studies of the composition of the residual atmosphere of a vacuum chamber when it is pumped out by an orbitron pump (Fig. 3), the following should be indicated.

Since the gas that is pumped out of the vacuum chamber is air, the main components of the air – nitrogen, oxygen, argon, and water vapor – will be present in its residual atmosphere. The air mass spectrum contains five main mass spectrometric peaks with masses of 28 amu. (100 %), 32 amu (27 %), 14 amu (6 %), 16 amu (3 %) and 40 amu (1 %), which belong to the N_2^+, O_2^+, N^+, O^+ and Ar^+ ions, respectively, (the intensities of the peaks relative to the intensity of the N_2 peak are shown in brackets) and the peaks with masses of 18 amu and 17 amu, which belong to the ions H_2O^+ and HO^+, respectively. In the absence of a leak in the mass spectrum of the residual atmosphere, the ratio of peak intensities will depend primarily on the type of high-vacuum pumps used. The appearance in the mass spectrum of peaks of other gases will depend both on the type of high-vacuum pumps used and on the degree of degassing of the walls of the vacuum chamber, the materials used in the construction of the vacuum installation, the temperature of the walls of the chamber and other components of the vacuum system.

The mass spectrum of residual gases when a vacuum chamber of a UVBL-6 unit is pumped out with a magnetic-discharge pump NMD-0.16 (Fig. 3a) with a maximum vacuum in the chamber $P = 2 \cdot 10^{-7}$ Pa is fairly simple. The main mass spectrometric peaks are the peaks of molecular H_2O water vapor ions with $M = 18$ amu, the peaks of fragments of its molecules with $M = 17$ amu (HO) and $M = 16$ amu (O). Since magnetic discharge pumps have significant pumping selectivity (the N_2 and O_2 active gases are pumped out much better than the inert gases (He, Ar)), there is a peak in the mass spectrum with $M = 32$ amu (O_2) is absent, however there are peaks with $M = 4$ amu (He) and $M = 40$ amu (Ar). Peak with $M = 2$ amu (H_2) mainly appears in the mass spectrum due to the fragmentation of the H_2O molecule in the ion source of the mass spectrometer. Mass spectrometric peaks with $M = 28$ amu and $M = 44$ amu belong to CO and CO_2, respectively.

These gases appear in the composition of the residual atmosphere of the vacuum chamber mainly as a result of their desorption from its walls.

Fig. 3b shows the mass spectrum of the residual atmosphere of the heated UVBL-6 vacuum chamber cut off from the pumps after it has been pumped out by the NMD-0.16 pump in the absence of a leak. The main mass spectrometric peaks are the peaks of molecular hydrogen ion H_2, carbon oxide and carbon dioxide CO and CO_2. There are also significant peaks of inert gases He and Ar, an insignificant amount of water vapor H_2O, and peaks of fragments of molecules CO and CO_2. Such a composition of the residual atmosphere is the result of gas evolution from the walls of the vacuum chamber (H_2, CO and CO_2) and the selectivity of air evacuation by a magnetic-discharge pump.

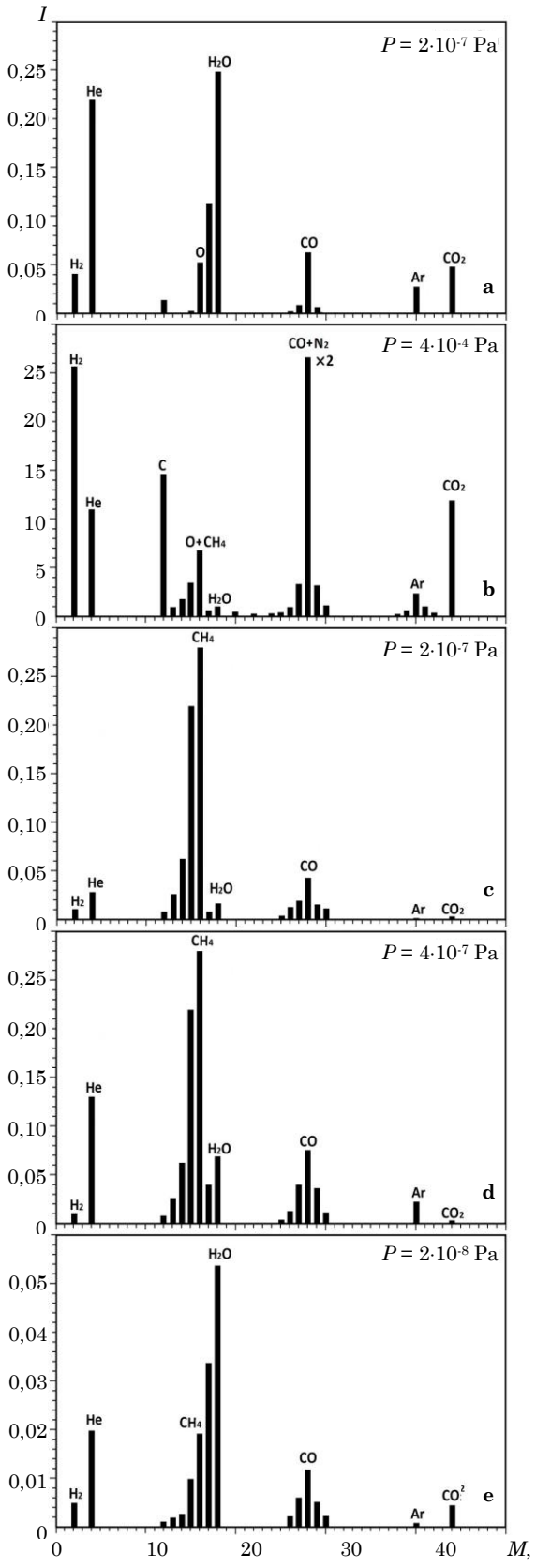

Fig. 3 – Mass spectra of the residual atmosphere of the vacuum chamber when it is pumped out by a magnetic-discharge pump (a); water cooled orbitron pump (c); orbitron pump in the "watchdog" mode (d); orbitron pump with nitrogen cryopanel (e) and vacuum chamber cut off from pumps (b)

Fig. 3c shows the mass spectrum of the residual atmosphere of the UVBL-6 vacuum chamber at a pressure $P = 2 \cdot 10^{-7}$ Pa in it when it is pumped out by an orbitron pump in its main operating mode ($U_A = 7.5$ kV, $I_A = 25$ mA, $I_k = 2.6$ A, $U_b = 50$ V, the power consumption in the anode circuit is about 200 W) with water cooling of its walls. The main component of the residual atmosphere is (as expected) methane CH_4 with $M = 16$ amu. Its quantity determines the limiting pressure in the chamber at room temperature $T = 290$ K of the sorbing titanium film.

When the orbitron pump is transferred to the "watchdog" mode ($U_A = 2$ kV, $I_A = 5$ mA, $I_k = 2.4$ A, the power consumption in the anode circuit is about 10 W), the pump maintains a vacuum in the chamber $P = 4 \cdot 10^{-7}$ Pa. From the mass spectrum of the residual atmosphere (Fig. 3d) we see that its main component is again methane as well as inert He, which, under this mode of pump operation, is practically not pumped out.

The most interesting is the mass spectrum of the residual atmosphere of the vacuum chamber at a pressure $P = 2 \cdot 10^{-8}$ Pa in it (Fig. 3e) when it is pumped out by an orbitron pump in the same basic operating mode, but using nitrogen cryopanel. Now the gas that determines the ultimate vacuum in the chamber is water vapor H_2O, and not methane CH_4. In our opinion, the reason for this is a significant decrease in the intensity of the chemical reaction of methane synthesis on the surface of the sorbing titanium film when it is cooled to $T = 77$ K compared to $T = 290$ K, since pumping methane with a titanium film and at $T = 77$ K (Table 2) is ineffective.

From here one can make an extremely important conclusion in practical terms – since water vapor molecules appear in the gas atmosphere of a vacuum chamber only as a result of desorption from its walls, as a result of careful chamber degassing by prolonged heating to 250-300°C using an orbitron pump with nitrogen cryopanel and further improvements in her vacuum.

The main difference between the mass spectra of the residual atmosphere of a vacuum chamber with an "oil-free" vacuum (Fig. 3) and an "oil" vacuum [3, 7] is the complete absence of peaks with $M > 44$ amu in the mass spectrum of an "oil-free" vacuum (molecules of heavy hydrocarbons and their fragments).

Thus, the orbitron pump with a nitrogen cryopanel created by us is an effective pumping tool for creating a super-high oil-free vacuum (preferably 10^{-8} Pa (10^{-10} Torr)) in metal vacuum units that are fully heated.

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Високовакуумний насос орбітронного типу: електрофізичні принципи роботи та особливості конструкції

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У статті представлені результати досліджень роботи орбітронного гетерно-іонного вакуумного насоса (ОГІН) з азотною кріопанеллю. У роботі наведено розраховані середні значення питомих швидкостей відкачування різних газів плівкою титану. Особливістю ОГІН є те, що в ньому електрони емітовані термокатодом використовуються як для розігріву і сублімації Ti, так і для іонізації газових молекул. Активні гази відкачуються завдяки хемосорбції неперервно відновлюваної титанової плівки, інертні гази – внаслідок іонізації їх атомів електронами, що рухаються в порожнині насоса, подальшого прискореного руху утворених іонів до стінки корпусу насоса їх імплантацією в титанову плівку й „замуровуванням" у ній атомів Ti, що осідають. Тими ж прискореними електронами іонізується і певна частина молекул активних газів та молекули важких вуглеводнів, які також сорбуються титановою плівкою. У статті також описані конструктивні особливості ОГІН та режими його роботи. За допомогою мас-спектрометра MX7304A вивчений склад залишкової атмосфери вакуумної камери при її відкачуванні до надвисокого вакууму у залежності від режимів роботи ОГІН. Установлено, що основною особливістю мас-спектрів залишкової атмосфери вакуумної камери при її відкачуванні ОГІН є повна відсутність у мас-спектрах піків з $M > 44$ а.о.м. (молекул важких вуглеводнів). Основною складовою залишкової атмосфери при водяному охолодженні ОГІН є метан CH_4, кількість якого і визначає граничний вакуум у камері. При використанні азотної кріопанелі основною складовою залишкової атмосфери є водяна пара H_2O. Зроблено висновок, що зконструйований ОГІН з азотною кріопанеллю є ефективним відкачуючим засобом для створення надвисокого безмасляного вакууму в металевих вакуумних установках, які повністю прогріваються.

Ключові слова: Надвисокий безмасляний вакуум, Орбітронний гетерно-іонний вакуумний насос, Мас-спектр залишкової атмосфери.