Gas dynamic characteristics of glow discharge chamber for functional coating deposition.

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Abstract. In article shown conditions of glow discharge existence at low pressures. Described possibility of organizing glow discharge at very low pressures due to the supersonic gas flow in a limited area of the discharge chamber. Procedure of supersonic flow regime calculating in vacuum chamber for coating deposition shown.

1. Relevance
Field of glow discharge application for plasma processing of details surfaces continuously expanding. Ion-plasma sputtering of the material or modification of surfaces is increasingly used in optic industry, electronics and other fields. One of new area is additive technologies.

In ion-plasma technological process is necessary to organize smooth achievement of the particles to processing surface. To achieve this condition free path length \( \lambda \) of particles should be several times larger than the distance \( L \) from the area of movement beginning to processing surface.

One of conditions for glow discharge existence is presence of all near-electrode zones. Length of each zone is determined by the number of collisions of an electron with neutral particles. With pressure decreasing length of cathode zones is increasing and certainly there comes a time that the electrode gap is not enough space for all near-electrode zones. Therefore, at very low pressures, the discharge can not exist. To find the critical pressure, at which it is still possible glow discharge, we assume condition of cold discharge. We assume that inter-electrode distance of 10 cm and number of collisions 10, so mean of free path \( \lambda \) is 1 cm. Calculate critical pressure for existing of glow discharge \([1]\):

\[
P_c = \frac{k_v T}{\sqrt{2 \cdot \lambda \cdot \sigma}} = 4.2Pa = 3.15 \cdot 10^{-2} Torr
\]  

Thus, existence of glow discharge at pressures below \(10^{-2}\) Torr hampered. Therefore, there is an insoluble problem: on one side discharge existence pressure above \(10^{-2}\) Torr is necessary and from another glow discharge application in technological processes of coating deposition required pressure below \(10^{-2}\) Torr.

One solution to this problem is magnetron sputtering application \([1, 2, 3]\). Magnetic field may increase the probability of collision of electrons with neutral atoms to order more times at low pressures by the joint action of electric and magnetic fields on moving charges. All this gave opportunity to magnetron discharge application at a pressure of about \(10^{-3}\) Torr. That led to a widespread of magnetron systems in installations for ion-plasma treatment.
In works [4-7] is proposed a fundamentally new solution to problem. Namely, they proposed the creation of zones of different concentrations of neutral particles in electrode gap. For example, in cathode area to create a high vacuum with a minimum concentration of neutral particles, in anode area to provide a relatively high concentration of neutral particles. Electrons in region with high concentration of neutral particles can experience dozens of collisions with neutral particles, while the processing of the material will take place at the maximum possible low pressures. For this condition, it is necessary to create a stream with particles of the working gas in the interelectrode space and at the same time to maintain the vacuum in the discharge chamber below $10^{-2}$ Torr. To achieve such a separation of zones in the electrode gap may allow the supersonic gas flow. The density of pumped gas through the working area should provide more than a dozen collisions of electrons with neutral particles, which will allow maintaining the glow discharge, keeping chamber pressure below $10^{-2}$ Torr.

To maintain different particle concentrations in chamber device shown (Fig. 1), providing the organization with a continuous supersonic flow and its pumping from the vacuum chamber using a supersonic nozzle and mixing chamber. In mixing chamber, flow restore and removed after by vacuum pump. At certain conditions device can operate as a jet pump that will not only keep the initial chamber pressure, but also lowering it.

![Fig. 1 Vacuum chamber with organization of different particle concentration.](image)

- RV - rotary vacuum pump, EV - valve, VB - valves box, PK - prev vacuum chamber, DOV - diffusion vacuum pump, ML - oil trap, VL - nitrogen trap, R - vacuum chamber, T1, T2 - thermocouple vacuum gauges, P - high vacuum gauge.

The aim of this work is to determine required conditions of supersonic flow and calculate system diffuser-confusor for supersonic gas flow regime creation in nozzle and mixing chamber.

Nozzle and mixing chamber consists of a diffuser and confusor parts and passage of critical cross-section flow velocity reaches critical speed, with the further expansion of flow occurs the growth rate.
In calculation of nozzle, main dependencies deduced from analysis of equations of flow continuity and the first two laws of thermodynamics [7].

2. Calculating and results
Calculating mixing chamber geometric parameters and operating gas flow regimes in supply system, field of continuous flow and pumping will allow carrying out pilot studies to obtain a new coating method in vacuum.

The calculations carried out in MathCAD.

Calculations [8] need to start with gas flow regime determining by comparing the differential pressure inlet and outlet of the nozzle. To start we define input pressures $P_{in}$ and $P_{out}$ of the output of the nozzle. It is necessary to receive the supersonic flow with diameter of 5 mm, while for 10 collisions, requires mean free path of electrons $\lambda_e$ more than 0.5 mm, using (1) we obtain $P_{out}$:

$$P_{out} > \frac{k \cdot T}{\sqrt[2]{\lambda_e \cdot \sigma}} = 85 Pa = 64 \cdot 10^{-2} Torr$$

Determine $P_{cam}=0.5Pa$, as a pressure of magnetron coating deposition. To determine $P_{in}$ use the formula for determining differential pressure $\beta_{out} = \frac{P_{out}}{P_{in}}$, and to obtain supersonic flow is necessary that the differential pressure was lower critical $\beta_{out} < \beta_{cr}$, which is calculated:

$$\beta_e = 2 \sqrt[2]{\frac{k}{k-1}} = 0.53 \quad (2)$$

From (2) we see that critical pressure ratio is only the physical properties of gas function. In this case, operating gas air, for which the adiabatic index $k = 1.4$, gas constant $R = 208 J / (kg \cdot K)$, from where $P_{in} > 170 Pa \cdot$ a, assign $P_{in} = 100 000 Pa$, approximately equal to atmospheric pressure.

For a given pressure differential obtain $\beta_{in} = \frac{P_{in}}{P_{out}} = 0.00085$, a condition $\beta_{out} < \beta_{cr}$ satisfied. Given that the pressure $P_i$, along axis of nozzle will be reduced from $P_{in}$ to $P_{out}$, we obtain:

$$\beta_i(P) = \frac{P_i}{P_{in}} \quad (3)$$

Initial temperature $T_0$ take as a normal 293 K and considering that operating gas temperature along the length of of the nozzle is reduced, define $T_i$ at every point along axis of nozzle:

$$T_i(P) = T_0 \cdot \beta_i(P)^{\frac{k-1}{k}} \quad (4)$$

Specific volume is calculated using the ideal gas law (5) and density reciprocal of the specific volume (6):

$$v_i(P) = \frac{R \cdot T_i(P)}{P_i} \quad (5)$$

$$\rho_i(P) = \frac{1}{v_i(P)} \quad (6)$$

Define flow velocity along axis of the nozzle:

$$a_i(P) = \frac{2 \cdot k}{k-1} \cdot \sqrt{R \cdot T_i(P)} \quad (7)$$

Local sound velocity (8) and Mach number $M_i$ - ratio of flow rate to local sound velocity in it:

$$a_i(P) = \sqrt{R \cdot T_i(P)} \quad (8)$$

$$M_i = \frac{w_i}{a_i} = \frac{1.97}{1.97} = 1$$

Knowing $M < 1$ - subsonic flow; $M = 1$ - sound flow; $M > 1$ - supersonic flow, we define supersonic flow.

Through cross-sectional area of the nozzle $f_i$ define diameter of the nozzle $d_i$:

$$f_i(P) = \frac{G}{\rho_i(P) \cdot a_i(P)} \quad (9)$$

Gas consumption defined through characteristic of the used vacuum pump 2NVR-5DM with ultimate total pressure $P_u=5 \cdot 10^{-3}$ Torr, pumping speed $G = 5.5 \ l/s$. By use coefficient 0.95 at 1 Torr pressure get $G = 4.9 \ l/s$, knowing density of operating gas at the outlet of the nozzle $P_{out}=85 \ Pa$ translate consumption in $3.81 \cdot 10^{-5}$ kg/s.
To calculate length of confusor \( l_{ci} \) and diffusor \( l_d \) of nozzle find full critical pressure \( P_{cr} \) and the critical diameter \( d_{cr} \), through the critical cross-sectional area \( f_{ccr} \):
\[
P_{cr} = \beta_c \cdot P_{fin} = 5.28 \times 10^6 \text{ Pa}
\]
We obtain \( d_{cr} = 0.453 \text{ mm} \). Confusor angle of nozzle take \( \alpha_{in} = 45^\circ \), diffusor angle \( \alpha_{out} = 30^\circ \):
\[
l_i = \frac{d_i - d_a}{2 \cdot \tan(\frac{\alpha_{in}}{2})} = 3.06 \text{mm}
\]
\[
l_o = \frac{d_i - d_a}{2 \cdot \tan(\frac{\alpha_{out}}{2})} = 4.72 \text{mm}
\]
Full length of nozzle is \( l = l_i + l_o = 7.78 \text{ mm} \).

To calculate mixing chamber parameters it is necessary to know pressure at its output. To carry out this characteristics of gas pumping system from the vacuum chamber and operating gas calculated. Pumping system, consisting of piping system and pump, should have enough bandwidth to provide supersonic flow rate in a vacuum chamber with pressure lower than \( 10^{-2} \) Torr.

To determine mixing chamber parameters it is necessary known provided by pump inlet pressure \( P_i \) in pumping system, considering flow resistance and flow rate \( G \).

The pumping system consists of three pipeline diameter \( Dn = 25 \text{ mm} \), length \( m L_i = 0.5, L_o = 1 \text{ m}, L_d = 0.5 \text{ m} \) along the length of the system from the pump up to chamber has two rotatings \( 90^\circ \) and valve. After calculations [18] determine total conductivity of the pumping system \( U_i = 154.7 \text{ L/s} \):
\[
S_{cr} = \frac{S_i \cdot U_i}{S_o + U_i} = 4.84 \text{ L/s}
\]
\[
P_i = \frac{G}{S_{cr}} + P_i = 138.3 \text{ Pa}
\]

So pump can provide the maximum flow rate of the mixed gas 4.84 L / s at an outlet pressure of mixing chamber 138 Pa. To define parameters of mixing chamber, pressure difference across the inlet and outlet calculated:
\[
\beta_c = P_i/P_{out} = 1.65 \text{ (10)}
\]

From (10) comparing differential and critical pressure, define \( \beta_c > \beta_{cr} \), therefore, there is a subsonic flow regime. Rate of the mixed flow velocity \( \omega_i \) at the outlet of confusor is (11):
\[
\omega_i = \sqrt{\frac{k}{k-1} \frac{R \cdot T_i(P_i) \cdot (\beta_c^{-\frac{1}{k}} - 1)}{\gamma}} = 109.34 \text{ m/s} \text{ (11)}
\]

Rate of critical mixed flow velocity \( \omega_{ccr} \) (12) and Specific critical volume \( v_{ccr} \), are (13):
\[
\omega_{ccr} = \sqrt{\frac{k}{k+1} \frac{P_{cr}}{v_c(P)} = 113.28 \text{ m/s}} \text{ (12)}
\]
\[
v_{ccr} = \frac{v_c(P_{cr})}{\beta_{ccr}^\frac{2}{3}} = 919 \text{ m}^3/\text{kg} \text{ (13)}
\]

Minimum cross sectional area \( f_{ccr} \) and diameter \( d_{ccr} \) of mixing chamber are:
\[
f_{ccr} = \frac{G}{\omega_{ccr}} = 27.82 \text{ mm}^2
\]

Area of inlet cross-section adopt as \( f_{inc} = 2 \cdot f_{ccr} = 55.4 \text{ mm}^2 \), diameter of inlet \( d_{inc} = 8.4 \text{ mm} \).

3. Conclusion

After calculations, nozzle and confusor geometric parameters and gas flow regimes in supply and pumping region of the continuous supersonic flow are determined. Defined steady pressure in the gas stream for confusor and cathode region. Specific parameters for this case were as follows: pressures inlet and outlet of nozzle \( (P_{inc}, P_{out}) \) and \((P_{out}, P_i)\) of mixing chamber, also their geometric characteristics.

Area of inlet cross-section adopt as \( f_{inc} = 2 \cdot f_{ccr} = 55.4 \text{ mm}^2 \), diameter of inlet \( d_{inc} = 8.4 \text{ mm} \).

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