Study of gas dynamic flow regimes in RFPT technological processes

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Abstract. Experimental measurements of the pressure in the vacuum chamber of the RF plasma unit at various flow rates of the working gas — Argon — have been carried out, and a dynamic vacuum curve has been constructed for the system. A simulation of the flow of working gases in a vacuum chamber in a COMSOL Multiphysics package was carried out at different flow conditions in the pressure range of 1–100 Pa, the dependence of pressure on flow was established, and the calculated data were compared with experiment.

1. Introduction

In the modern level of development of technology and technology, various processes carried out at low pressures in the range of 1 100 Pa are widely used, such as: high-frequency plasma processing (RFPT) processes, chemical gas-phase deposition and synthesis processes, thermal vacuum processes [1,2]. The scientific and technological interests of the authors of the article are RFPT technological processes, among which we can distinguish the technological tasks of plasma-physical (adhesive activation, cleaning, polishing, gas saturation) and plasma-chemical (etching with various RF gas discharge schemes) of surface treatment of materials. All the mentioned technological processes are sensitive to various irregularities of gas-dynamic conditions, therefore, when developing new technical processes and equipment, special attention should be paid to the modeling of gas-dynamic flows occurring in the working volume of the vacuum chamber, to evaluate the non-uniformity of the parameters of the gas environment and optimize the design of the components of the equipment, allowing to improve manufacturability production or provide specified requirements for processing facilities.
### 2. Modes of flow of rarefied gases

All laws of gas dynamics based on the continuum model are valid as long as the D’Alembert – Euler postulate is valid or, in other words, it is legitimate to use the continuum model to describe the motion of a real gas. The quantitative limits of the applicability of the laws of gas dynamics based on the continuum model are determined by the value of the Knudsen criterion, which is the ratio of the mean free path of gas molecules $\lambda$ to the characteristic size of the system $d$: $Kn = \lambda / d$. Depending on the value of the Knudsen criterion, the flow of gases is divided into two fundamentally different areas [3]:

1) $Kn < 0.01$ – continuum flow (laminar flow). It holds all the laws of gas dynamics of a continuous medium. The velocity and temperature of the gas (liquid) at the surface of solids is equal to the velocity and temperature of this surface. The laminar flow is described by the Poiseuille law, which is one of the simplest exact solutions of the Navier – Stokes equations.

2) $Kn > 0.01$ - flow becomes rarefied. There are 3 types of flow:
   - $0.01 < Kn < 0.1$ – slip flow. The Prandtl sticking hypothesis ceases to work in this region of the flow of not very rarefied gases. The gas at the surface of the body has some finite velocity. Gas temperature also differs from body temperature by a finite amount. In analysing the flow of gases in this area, the same equations of gas dynamics of a continuous medium are used with amendments to speed and temperature jumps;
   - $0.1 < Kn < 10$ – the transition region, the least studied area of flow of rarefied gases;
   - $Kn > 10$ – free molecular flow. The gas consists of individual molecules moving at different speeds according to the Maxwell distribution. Collisions with walls prevail over intermolecular ones. Separate molecules interact with the bodies and the calculation of this interaction is made by the methods of statistical physics.

In some literature, other regime boundaries are often used. Thus, the viscous regime appears at $Kn < 0.005$, the free molecular mode – at $Kn > 1/3$ [4,5].

### 3. Description of the task

The experimental setup (shown in Figure 1) is designed for ICP processing of various materials and is a modernized vacuum chamber of the UVN-71 with a diameter of 500 mm, to which the unit based on the AVZ-20D backing pump and booster NVD 600 is connected via the vacuum main Dn100 мм. Plasma-forming gas, argon, is supplied by means of a mass flow regulator RRG-10-360 through a quartz plasmatron with a diameter of 27 mm installed on the bottom plate of the chamber. The location of the vacuum gauges is shown in Figure 1.

![Figure 1. The scheme of the experimental setup.](image-url)
4. Results
The values of the Knudsen criterion for different sections of the vacuum system were determined and
the dependence of the gas flow regime on the pressure in each pipe was established (Table 1). The
mean free path of atoms is calculated in accordance with [2]. In a vacuum chamber, the gas flow
regime is laminar for almost the entire pressure range, only at pressures below 1 Pa it becomes transient.

Table 1. Knudsen criterion values for different sections of the vacuum system of different diameters *.

| Pressure (Pa) | Intake (d=7mm) | Plasmatron (d=27mm) | Vacuum line (d=100mm) | Chamber (d=500mm) |
|--------------|----------------|---------------------|-----------------------|-------------------|
| 0.1          | 9.500          | 2.436               | 0.665                 | 0.133             |
| 1            | 0.950          | 0.246               | 0.067                 | 0.0133            |
| 10           | 0.095          | 0.025               | 0.007                 | 0.0013            |
| 20           | 0.048          | 0.012               | 0.003                 | 0.0007            |
| 30           | 0.032          | 0.008               | 0.002                 | 0.0004            |
| 40           | 0.024          | 0.006               | 0.002                 | 0.0003            |
| 50           | 0.019          | 0.005               | 0.001                 | 0.0003            |
| 60           | 0.016          | 0.004               | 0.001                 | 0.0002            |
| 70           | 0.014          | 0.004               | 0.001                 | 0.0002            |
| 80           | 0.012          | 0.003               | 0.001                 | 0.0002            |
| 90           | 0.011          | 0.003               | 0.001                 | 0.0001            |
| 100          | 0.010          | 0.002               | 0.001                 | 0.0001            |

* bold - free molecular flow, double underline - transitional flow, underline – slip flow, the rest - continuum flow

Numerical simulation of currents was carried out under stationary conditions in the CAE package
COMSOL Multiphysics, modules Laminar Flow, Slip Flow, Transitional Flow, Free Molecular Flow.
Created solid model corresponding to the size of the experimental setup. The boundary conditions are set: argon consumption through the lower section of the plasmatron (Inlet / Diffuse Flux function) and
the passport characteristics of the pumping speed of the NVD-600 pump at the output of the vacuum line. Measurement of pressure in the numerical simulation was carried out in the same sections where vacuum gauges were installed on a real installation.

The simulation results in Laminar Flow and Slip Flow modes are absolutely identical. When calculating in the Transitional Flow module, due to the complexity of the computational domain and
the equations to be solved, it was not possible to achieve convergence of the solution with acceptable
accuracy. Increasing the accuracy of the calculation in this solver requires an increase in the number of nodes of the computational grid, which would entail a significant increase in the estimated PC
resources. Molecular Flow was used to compare the results of calculations of various mathematical
models. The results of numerical simulation and experiment are presented in Figure 2.
5. Conclusion

The results of numerical simulation and experiment are approximated with high accuracy by a straight line. The tangent of the slope of the experimental and calculated lines is different, which causes an increase in error with increasing pressure in the system, but the calculation error in the pressure range of 1-100 Pa does not exceed 15%, which is acceptable when designing and forecasting technological processes.

It is noted that in the numerical simulation, the pressure drop from the chamber to the pipeline does not exceed 1 Pa, which is inconsistent with the experiment, where the difference is 2-3 Pa. This discrepancy can be explained by the presence of local resistances (narrowings, turns) of the line at the installation site of the vacuum gauge, which significantly reduces the conductivity, which depends on the diameter in the third degree.

The results of numerical simulation showed sufficient convergence with experimental data in the considered range of 1-100 Pa. For pressures in excess of 100 Pa, it is possible to use numerical results with the introduction of correction factors.

6. References

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