INVESTIGATION OF THE INPUT CHANNEL OF A DIFFUSION PUMP

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The flow in the input part of a high-vacuum diffusion pump is studied experimentally and with the help of Monte Carlo modeling.

Introduction and Formulation of the Problem. The Monte Carlo method is now the main method of mathematical modeling of molecular flows. The literature contains numerous examples of the calculation of the conductance and structure of a flow in complicated vacuum systems [1]. In the solution of a specific problem there always arises the question of the correspondence between the results obtained and the real conditions. Without discussing the assumptions that cause the calculations to differ appreciably from the experimental data, we point out that there are very few experimental data for testing calculations, and this often makes it necessary to perform expensive tests of real apparatus.

In this paper we comapre the results of experimental and numerical investigations of flow in the input part of a high-vacuum diffusion pump. The calculation was performed by the Monte Carlo method and the experimental measurements were performed with the help of pneumatic electric sensors. The specific technical orientation of these studies does not limit their generality.

Works devoted to the numerical modeling of flow in the inner part of a pump, for example [2], have occasionally appeared in the literature. The development of apparatus with a flow-through part with a new geometry has made it ncessary to optimize the input part of the pump. Up to now the possibilities of optimizing pumps with a shaped housing, expanded in the region of the nozzle in the first stage, have not been studied [3]. One of the main advantages of such pumps is the weak return flow of the vapors of the working body (in the evacuated volume). Another important advantage, studied in [4], is the possibility of obtaining a high relative speed (vacuum factor) $f = S/S_0$, where S is the speed of the pump (the volume rate of pumping) and S_0 is the maximum possible volume flow rate through the input opening in the molecular regime.

The problem addressed in the present numerical and experimental investigations was to determine the value of f and the distribution of the parametes of the gas in a given section for a specific geometry of the channel in the first stage of the pump.

Figure 1 shows the contours of the flow-through part of the pump adopted in the calculation for the following formulation of the conditions: the "pumped" gas flows in through the flat surface I and exists through the annular surface V, which is assumed to trap completely the molecules reaching it. The dot-dashed line in Fig. 1 shows a possible trajectory of the molecules.

Computational Method. The flow in the inlet channel was modeled for the free-molecular regime, i.e., neglecting the intermolecular collisions; it was assumed that the molecules appearing on the side of the evacuated volume are uniformly distributed over the area of the cross section I (Fig. 1) and they have an isotropic Maxwellian velocity distribution.

The start of a test particle was modeled with the help of the procedures of the Monte Carlo method. The initial radial position of the particle was determined according to the dependence $r = R\sqrt{A}$, where R is the radius of the input section of the pump and A is a random number distributed uniformly in the interval (0, 1) [5]. The initial velocities of the molecules are played out according to a Maxwellian distribution as follows. Let A, A_1, and A_2 be random numbers distributed uniformly in (0, 1). Then according to [6]

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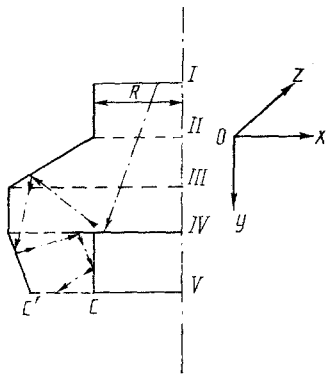

Fig. 1. Computational diagram of the flow-through part of a high-vacuum pump.

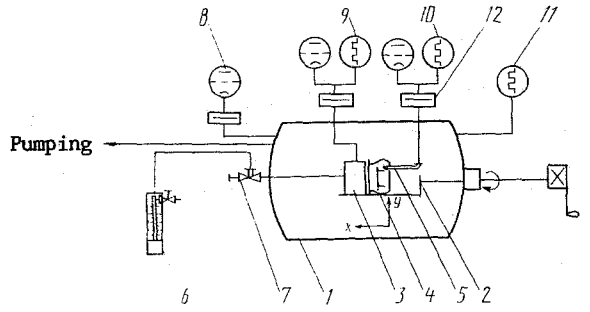

Fig. 2. Diagram of the experimental apparatus: 1) vacuum chamber; 2) two-way coordinate spacer; 3) measuring cowl; 4) element of the flow-through part of the pump; 5) pneumatic type probe; 6) measuring buret; 7) flow regulator; 8-12) manometric pressure transducers.

$$v_y = \sqrt{-\ln A},\ v_x = \sqrt{-\ln A_1}\cos(2\pi A_2),\ v_z = \sqrt{-\ln A_1}\sin(2\pi A_2).$$

The proposed method for modeling the trajectory of a test particle consists of studying its motion up to the nearest characteristic plane y = const in accordance with the direction of the velocity v_y. The intersection of the particle trajectory withe ach of the planes I, II, III, IV, and V determines the radial distance form the axis, whose magnitude makes it possible to establish the possibility of the test particle striking the wall of the pump. Analysis of a limited collection of surfaces y = const greatly simplifies the algorithm for choosing the quadric surface with which the test particle collides. This saves computer time. The coordinates of the point at which the particle strikes the pump wall are determined by solving simultaneously the equations of a quadric surface and the straight line along which the particle moves. Two types of interaction of molecules with the pump walls were studied: mirror and diffuse reflection with full accommodation of the molecules on the surface of the wall in the case of the diffuse reflection of molecules at the pump walls, and the velocity of the test particle after the collision is determined with the help of the Monte Carlo procedure. The trajectory of each test particle is followed until it reaches the surface V or the particle escapes in the opposite direction through the input section I. The ratio of the number of molecules reaching the surface V to the total number of starting molecules is taken to be the conductance of the input channel of the pump. Since the further motion of test molecules is not studied the value of the Clausing coefficient calculated in this manner can be used as the upper limit of the vacuum factor f. The calculation was performed for 10^6 molecules and required one hour of computing time on the ES-1061 computer.

Experimental Procedure. The idea of the experiment consisted of blowing gas through the input apparatus under study (Fig. 1), the radius of whose input opening R = 50 mm, under close to free molecular conditions. A cowl was attached in the plane I to the element under study in order to measure the pressure at the inlet, while a pressure significantly lower than in the cowl was established at the outlet from the channel, i.e., in the vacuum chamber.

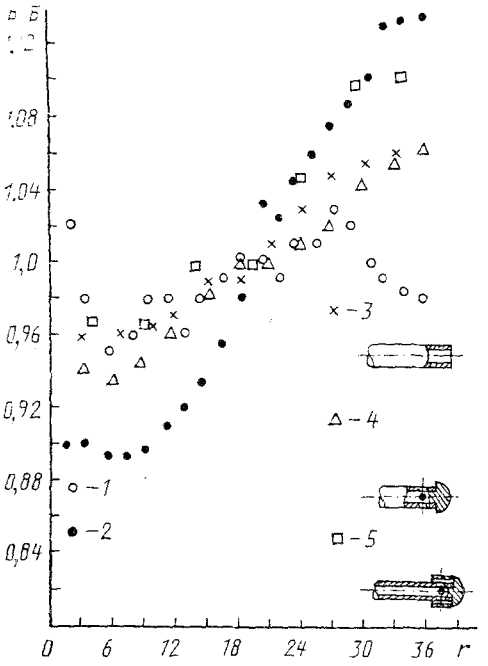

Fig. 3. Distribution of the pressure and density of molecular flows in the flow-through part of a high-vacuum pump (see Fig. 1) (in relative units): 1) calculation of the concentration of molecules; 2) calculation of the flux density of molecules; 3) experiment (Pitot's tube); 4) experiment (open static tube); 5) experiment (closed static tube). r, mm.

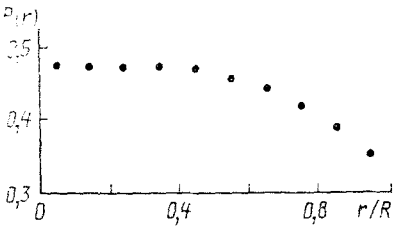

Fig. 4. Clausing coeficient versus the radial distance from the axis.

Figure 2 shows a diagram of the experimental arrangement. A measuring cowl 3 with an element of the flow-through part 4 is placed in the vacuum chamber 1, having a diameter of 1 m and a length of 1.4 m, on a two-way coordinate spacer 2. The gas pressure in the flow-through part is measured with the help of a pneumatic type receptor 5, connected to manometric transducers. The flow rate of the gas was determined with the help of a measuring buret 6 and a flow regulator 7. The numbers 8-12 indicate the manometric transducers for all necessary measurements – in the vacuum chamber, in the cowl, and in the pneumatic type measuring sensors. The vacuum chamber was evacuated with two AVP 160/250 oil-diffusion pumps.

The error in the placement of the sensor was equal to ±0.25 mm and the error in measuring the pressures in the cowl and the pneumatic type measuring sensor, according to sensors calibrated based on a standard class I apparatus, was equal to ±20%.

Analysis of the Conductance. In representing the experimental characteristics of the channel conductance we used Clausing's coefficient as the ratio of the channel conductance to the maximum possible conductance of the opening (for example, for air at room temperature U_{max} = 11.6 F, where U_{max} is given in liters/sec and the area of the opening F is given in cm^2). In the Monte Carlo calculations Clausing's coefficient was obtained automatically as the probability that a molecule released in the starting section I passes through to the given surface V.

The average value of Clausing's coefficient, obtained in the experiments as the result of separate blowings through the measuring cowl and the input part into pump together with the measuring cowl is $f \approx 0.5$.

The value of Clausing's coefficient determined by the standard Monte Carlo procedure for the case of diffuse reflection on the section from the input cross section to the cross section V is $f = 0.421$. For the case of mirror reflection $f = 0.55$. From here it follows that since the flow-through part of the computational model is virtually identical to the experimental flow-through part, the character of the collisions of the molecules with the wall is neither diffuse nor mirror.

It is important that there is no fundamental quantitative disagreement between the computational and experimental results.

Distribution of the Pressure in the Section Perpendicular to the Axis of the Annular Channel. The pressure distribution in the section V was determined from the indications of the VIT-3 apparatus with a PMI-2 ionization transducer. The flow in the channel studied can be assumed to be isothermal. But since the pressure signal is not isotropic it cannot be identified as the pressure at a point and doing so can introduce an inadmissible error. However in the case of relative measurements in some section with the orientation of the sensor held constant it is possible to obtain results with satisfactory accuracy. In this case the pressure signal can be assumed to be approximately proportional to the density of the gas molecules reaching the opening of the sensor. This assumption is adopted in this work in order to compare the experimental results with the calculations.

For the measurements we used pneumatic type sensors of three types (Fig. 3): Pitot tube and open and closed static-pressure tubes.

Figure 3 shows the radical distribuiton of the air pressure, obtained with the help of different tubes in the plane V between the points C and C'. The origin of the coordinates is placed at the point C'. The pressures are presented in relative units and normalized to the pressure at the average radius of the transverse section of the channel in the plane V, where all experimental values of the pressures coincided. To make it easier to compare with experiment the numerical results are also scaled to the corresponding values at the average radius. The probability that the molecules strike a unit area of the cross section V as a function of the radial distance from the axis was determined as follows. The section V from the point C to C' was divided into two rings, in each of which the quantity equal to the ratio of the number of molecules crossing this ring to is area was determined. We stressed that the calculation was performed for the free-molecular case and under the condition that the pressure in the chamber is equal to zero. This simplification was made in order to remain within the linear formulation of the problem (in the volume of the chamber the collisions between molecules cannot be neglected). Indeed, the experimental data were obtained for pressures in the measuring cowl of $1.33 \cdot 10^{-3}$-0.133 Pa and pressures in the vacuum chamber of $6.65 \cdot 10^{-4}$-$6.65 \cdot 10^{-2}$ Pa. Knudsen's numbers for the conditions of the experiment were equal to 0.5-50 in the cowl and 1-100 in the plane V; this means that at the higher pressures intermolecular collisions can also occur in the flow-through part of the system studied.

A methodical result of this part of the work that the indications of the apparatus with different sensor tubes differ insignificantly, and this difference is much less than the errors in the measurements.

The main result of the investigations of the radial distribution of the gas pressure is the conclusion that the nonuniformity of the molecular flows in the annular channel and the displacement of the maximum flows toward the periphery of the channel are insignificant.

Analysis. As one can see from Fig. 3, the experimental results and the calculations of the molecular flows agree qualitatively and even quantitatively. It should be noted that the indications of the pressure sensors most likely correspond to the molecular flux [7, 8], as is confirmed by the calculation, than the pressure. Figure 3 illustrates the quantity proportional to the computed concentration of molecules. Even its qualitative behavior, characterized by the strong nonuniformity over the cross section, deviates significantly from the indications of the pressure sensors in the experiment. The nonmonotonic nature of the indicated computed quantity (proportional to the pressure) can be explained by the significantly nonisotropic nature of the flow. In the calculation it was assumed that the residence time of the molecules in a unit volume at a definite distance from the axis is proportional to the density. Analysis of the calculations and the experimental data suggests that the

sensors measure a quantity that is a complicated superposition of the dynamic head and the static (background) pressure.

Effect of the Starting Point of the Molecules on the Channel Conductance. The possibility of direct statistical modeling of the flow in the channel makes it possible to determine the dependence of the conductance of the annular channel under study on the position of the starting point of the molecules in the plane I. Figure 4 shows this dependence in the form of the function P(r) for the case of diffuse reflection from the walls. The conductance depends strongly on the radius of the starting point of the molecules. The strong drop in the conductance for the peripheral zone of starting points of the molecules is not predictable a priori, which underscores the importance of the obtained result.

The average value of the channel conductance from the input section to the section V, found based on the data in Fig. 4, is the same as the value obtained using the standard Monte Carlo procedure.

The good agreement between the experimental data and the calculations shows that the Monte Carlo method can be used to calculate molecular flows in complicated annular channels, and the greater information content of the numerical calculations compared with the experiments shows that the Monte Carlo method has indisputable advantages for studying molecular flows in complex systems.

NOTATION

Here, f is the vacuum factor; S is the speed of the pump; S_0 is the maximum possible volume flow rate through the input opening in the molecular regime; r is the radial distance from the axis; R is the radius of the input section of the pump; A, A_1, and A_2 are random numbers distributed uniformly in the interval (0, 1); v_x, v_y, and v_z are components of the velocity of the molecule in the corresponding direction of the coordinate axes; u_{max} is the maximum possible conductance of the opening; F is the area of the opening; and, P(r) is the Clausing coefficient as a function of the radius.

LITERATURE CITED

1. G. L. Saksaganskii, Molecular Flows in Complex Vacuum Systems [in Russian], Moscow (1980).
2. J. N. Chubb, Vacuum, 16, No. 11, 591-596 (1966).
3. B. D. Power, N. T. M. Dennis, R. P. Oswald, and B. H. Colwell, Ibid., 24, No. 3, 117-122 (1974).
4. A. K. Rebrov, Collection of Works on Gas-Dynamics of Jet Vacuum Pumping Processes [in Russian], Novosibirsk (1985), pp. 7-20.
5. I. M. Sobol', Monte-Carlo Numerical Methods [in Russian], Moscow (1973).
6. G. Bird, Molecular Gas Dynamics [Russian translation], Moscow (1981).
7. A. V. Kosov, Collection of Works on Gas-Dynamic Processes of Jet Vacuum Pumping [in Russian], Novosibirsk (1985), pp. 20-40.
8. D. E. Rothe and J. N. de Leew, AIAA J., 1, No. 1, 220-221 (1963).