AERODYNAMIC WINDOW WITH A PRESSURE SEPARATION RATIO GREATER THAN 500

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The possibility of creating a two-stage aerodynamic window with a high pressure drop is demonstrated. The window consists of two gas channels with free vortex flow in each of them. It is shown that the gas exchange between the stages can be used efficiently to increase the working pressure drop of the window.

High-power laser radiation and particle beams are widely used in various plasma chemistry technologies in the mechanical and thermal processing of parts and materials. As a rule, laser radiation is generated in a resonator at much less than atmospheric pressure. Particle beams are created in the vacuum chamber of the accelerator. Therefore, in both cases the problem arises of getting the radiation or the beam into the atmosphere.

An experiment to create an aerodynamic window for extracting high-power laser radiation shows that windows, in which "free vortex" flow [1, 2] is used in the overlapping zone of the exit channel, minimize losses of the working gas. However, it has not been possible to attain pressure ratios $\bar{P}$ above 30-50 in the screen jets at these windows, because of the difficulty in providing the gas-dynamic startup of the gas channel and in effectively braking the stream of the working gas at the exhaust diffuser of the window [2-4]. In systems to extract particle beams from accelerators, it is fundamentally impossible to prevent part of the working gas from flowing along the exit channel into the vacuum volume. Therefore, in designing the gas channel of the window it is not only important to attain the maximum value of $\bar{P}$ for a minimum loss of the working gas through the window, but also to minimize the flow into the extraction channel. An additional requirement is a small length of the extraction channel, in order to exclude beam instability in the screen jet of working gas.

In order to solve this problem, we examined the possibility of using a two-stage high-pressure-drop aerodynamic window with free vortex flow in each stage. The conditions for creating the flow in each stage of this window are completely different, because the second, low-pressure stage operates at low Reynolds numbers (because the absolute values of the pressures which are separated by the jet are almost two orders of magnitude lower than for the first, high pressure stage, which is on the atmospheric side). Experiments show that this decrease in the Reynolds number leads to a large decrease in the pressure ratio $\bar{P}$ at the second stage, which becomes ever more significant as the Reynolds number is decreased. As a result, the efficiency of the low-pressure stage is decreased as the pressure ratio is increased in the high-pressure stage. Thus, the problem arises of optimizing the combined operation of the two stages, in order to attain the best characteristics of the window as a whole. In actual window constructions, the pressure ratio at the jet often does not agree with the value used to design the nozzle [1, 2]. This is explained by the large dependence of the aerodynamic window parameters on the configuration of the inlet section of the exhaust diffuser, which parameters determine the attachment conditions of the jet with the diffuser walls, and also the dependence on the magnitude and direction of the gas transfer at the inner and outer boundaries of the screen jet, which is related to the impossibility of calculating the pressures which arise at the end of the nozzle under actual conditions.

It has been shown [2] that evacuation of a very small amount of gas from the low-pressure zone or the addition (mixing) of gas into the high-pressure zone (at the level of a few percent of the working gas loss) substantially increases the value of $\bar{P}$ compared to the case of no gas transfer. This led to the idea of using this feature to realize an overall value of the pressure ratio $\bar{P}_{1,2}$ in a two-stage window which exceeds the product of the two quantities for each stage in the absence of gas transfer; that is, $\bar{P}_{1,2} > \bar{P}_1 \bar{P}_2$.

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The two-stage window was optimized experimentally, because calculating both operational features (the lowered Reynolds numbers and the gas transfer) currently is difficult.

For the investigation, we chose a window formed from two identical stages, with the use of "free vortex" flow at the screen. Their nozzles were profiled by the method used in [5] and were designed for a screen jet with a pressure ratio of $\overline{P} = P_+/P_- = 150$ at the boundaries for a relative total pressure at the nozzle inlet of $\overline{P}_0 = P_0/P_+ = 12.5$. The rotation angle of the jet, that is, the angle in the plane of symmetry of the window between the edges of the jet and the diffuser in the low pressure zone, was chosen to be 70°. The diameter of the outlet channel was 38 mm and the width of the gas jet was much larger, 52 mm, which guaranteed a distance of 7 mm between the channel and the side walls of the gas duct. The duct was formed by two coupled shaped parts, which created (in sequence) a gas channel in the form of a reverser, a plane nozzle, a zone with a free screen jet intersecting the exhaust channel, and the inlet section of the diffuser. The plane side walls were welded to the shaped parts along the gas duct, in order to guarantee a tight seal of the gas channel of each stage. The two-stage window was formed by two of these stages with a gap of 20 mm between them. The gas channels were mounted perpendicular to each other. The total length of the channel in this assembly was 150 mm. In conducting the tests, buffer volumes, in which various pressures could be maintained to simulate working conditions at the channel inlet and outlet, were attached to the ends of the channel. The working gas for the high-pressure stage was extracted from the diffuser directly into the atmosphere. The exhaust channel of the internal low-pressure stage was connected to a pumping system through a buffer volume. The gas supply system of the stand used to test the window could be varied in a wide range (almost four orders of magnitude) of the total pressure of the working gas of the window. The level of gas transfer between the jets of each stage and betweeen the window and the volumes separated by it could be similarly varied.

The basic difficulty in setting up the window tests was in providing the stand with methods to measure a wide range of both working gas pressures of 10^{-2}-10^{5} Pa and gas flows at the jet boundaries (0.1-2.0 g/sec) because of the short duration of the operations, which are limited by the time to fill the buffer volumes. Thus, we used a large number of intercalibrated pressure sensors, in particular VO-0.25 vacuum meters, a piezometric plate filled with VM-3 vacuum oil, an RVT-1m vacuum thermal relay with a PMT-6-3 transformer, and a VIT-3 vacuum meter with a PMI-10-2 transformers. Outputs were recorded on an S8-17 series IKD oscilloscope with NO30A recording oscillograms. The gas flow was determined by measuring the pressure in a given time interval in known buffer volumes and also by calibrating the flow throttles.

Two series of experiments were conducted. In the first we investigated in detail the operation of the first stage of the window over a wide range of Reynolds numbers with and without gas transfer from both sides of the working jet. In the other series we tested a two-stage window assembly to confirm the correct choice of combined operating conditions and to estimate the limiting pressure drops and flow into the vacuum volume of the assembly.

The choice of the operating regime of the two-stage window was based on tests of a single stage with a varying pressure P_0 from 10 kPa to 1.5 MPa for sealed buffer volumes on the side of P_+ and P_-, and also for feeding gas into the P_+ volume while pumping it out of the P_- volume (Figs. 1-5).

In a variant with sealed P_+ and P_- volumes and gas-dynamic startup, the ratio $\overline{P}_0$ rapidly reached a constant value of $\overline{P}_0 \sim 14.5$, which remained practically unchanged over a wide range of P_+. The operational drop of $\overline{P}$ monotonically decreased when P_+ was reduced. The value $P_+ = 100$ kPa corresponded to $\overline{P} \sim 20$, but when P_+ was reduced to 0.1 kPa, the drop of $\overline{P}$ was reduced to 2 (the open points in Fig. 1). When gas was mixed in the P_+ volume, $\overline{P}$ increased to a maximum at $\overline{P}_0 \sim 13$, and then dropped rapidly (Fig. 2). The maximum value of $\overline{P} \sim 50$ (Fig. 3) was obtained for the case where the end of the channel was completely opened to the atmosphere ($P_+ = 100$ kPa). When P_+ was reduced, the maximum value of $\overline{P}$ dropped (Fig. 1). For $P_+ = 2.5$ kPa, we found $\overline{P} = 20$, but for $P_+ = 0.5$ kPa, $\overline{P} \sim 5.0$ (filled points in Fig. 1). Over the whole investigated range, the maximum values of $\overline{P}$ obtained with mixing greatly exceeded values of $\overline{P}$ for the case without adding gas.

Pumping out gas from the P_- side greatly increased the pressure drop $\overline{P}$ (Fig. 4). For example, for $P_+ = 100$ kPa, pumping at a rate of $G_- = 0.6$ g/sec (0.2% of the gas mass flow through the nozzle) made it possible to increase $\overline{P}$ to 100, while for $G = 1.2$ g/sec, $\overline{P} \sim 270$.

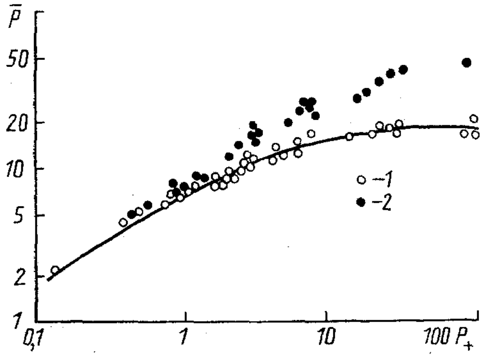

Fig. 1

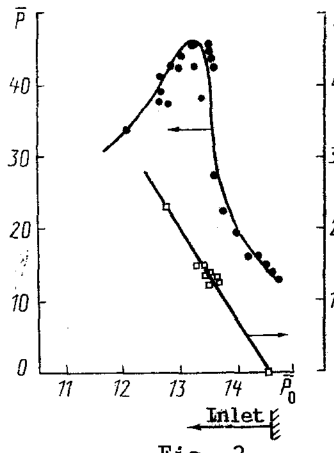

Fig. 2

Fig. 1. Dependence of the pressure drop $\bar{P}$ at the window stage on the pressure P_+: 1) volume on the P_+ side is sealed; 2) optimum gas inflow fed to P_+ side; P_+ in kPa.

Fig. 2. Effect of admitting gas G (g/sec) into the screen jet from the P_+ side on the attainable drop $\bar{P}$ (P_0 ~ 13 MPa).

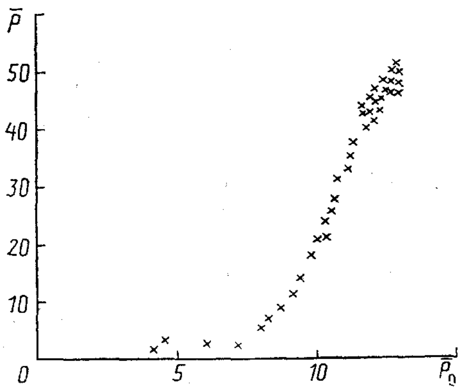

Fig. 3

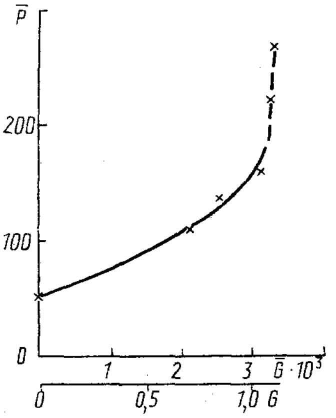

Fig. 4

Fig. 3. Dependence of the pressure drop $\bar{P}$ at the window stage on P_0 for the exhaust diffuser and a channel output open to the atmosphere.

Fig. 4. Effect of pumping out the P_- side on the pressure drop $\bar{P}$ at the window stage (P_0 ~ 13 MPa).

In order to evaluate the "blocking" effects of the aerodynamic window, it is convenient to use a dimensionless parameter which characterizes the flow reduction through the channel $\bar{G} = G_N/G$, where G is the gas flow actually flowing through the channel into the P_- volume when the window is operating, and G_N is the flow of gas through the output channel from the atmosphere (at the sound speed) if the window was not operating. Operational values of $\bar{G}$ agree well with the approximation $\bar{G}$ ~ $2\bar{P}$, where $\bar{P}$ corresponds to operation without pumping out gas from the P_- volume.

From data obtained in the investigation of the relation between the pressure drops from the window stage and the gas-transfer flow from the window jets, it follows that these effects can be used to create a two-stage window. The overflow of part of the working gas from the jet on the high-pressure stage into the exhaust diffuser of the low-pressure stage for the current stage design should improve the operating conditions for each stage and consequently increase the total pressure ratio of the two-stage window.

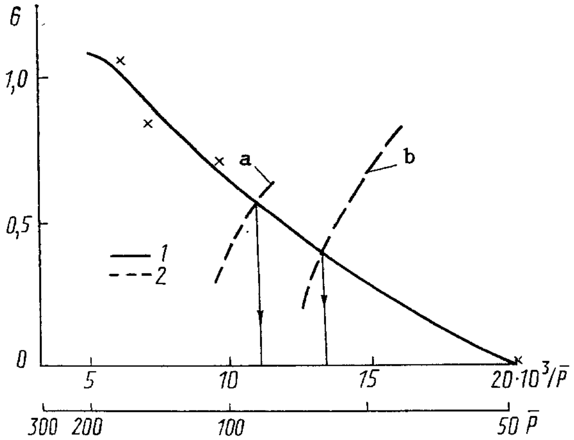

Fig. 5. Effect of gas transfer between stages on the operation of the high-pressure stage of the window (P_{01} = 13 MPa): 1) Pumping rate G from the screen of the high-pressure stage from the $(P_-)_1$ side; 2) inflow G into the low-pressure stage from the $(P_+)_2$ side; a) P_0 = 11.3 kPa; b) P_0 = 15.4 kPa.

By knowing how the pressure drop in the jet of the high-pressure stage depends on the pumping rate from the P_- volume and how the pressure drop of the low-pressure stage depends on the flow from the P_+ side, it is possible to estimate the conditions of combined operation.

An example of such an evaluation is shown in Fig. 5. Two conditions were examined for stationary operation of the inner stage: with P_0 = 11.3 kPa (85 torr) and P_0 = 15.4 kPa (116 torr) for a sealed P_- volume. It can be seen that the "equilibrium" gas transfer between the stages in the first case should be close to 0.55 g/sec, but in the second close to 0.35 g/sec. Data obtained for the corresponding P_0's show that under these conditions in the low-pressure stage, it is possible to attain a pressure drop of $\bar{P}$ = 6.6 and 7.8 respectively. Considering the pressure drop which can be attained under these conditions in the outer stage (90 and 75), a total pressure drop in the two-stage window of this design can be expected to be $\bar{P}_\Sigma$ = 590 and 580.

The actual results are rather close to these estimates, which indicates it is possible to use this approach for predicting the characteristics of two-stage windows based on autonomous investigations for each stage.

The final step of our effort was devoted to the direct verification of the operational efficiency of the two-stage window design and to refining the optimum conditions for combined operation of the stages. In this series of experiments, the high-pressure channel from the P_+ side and at the diffuser output was directly connected to the atmosphere. By selecting the total pressure at the input to the nozzle of the low-pressure channel, we tried to obtain the maximum value of $\bar{P}_\Sigma$ and the minimum flow into the P_- volume.

Two test cycles were conducted. In one, the P_- volume was sealed, in the second, the gas was pumped out of it into the vacuum system. The maximum value of $\bar{P}$ was 660, which was obtained in the first test cycle, and which was attained over a relatively wide range of the total pressure ratio at the nozzle input of the stages $\bar{P}_{00} = P_{01}/P_{02}$ = 70-80. Here the total pressure in the reservoir of the low-pressure stage was 12-15 kPa. The value of $\bar{P}$ was lowered to 600 for $\bar{P}_{00}$ ~ 65 and 105 and to $\bar{P}$ = 500 for $\bar{P}_{00}$ ~ 50 and 115.

Comparison with results obtained for an isolated stage leads to the conclusion that the maximum drop occurs for conditions where the overflow part of the gas from the jet of the high-pressure channel into the diffuser of the low-pressure stage is ~0.5 g/sec.

The maximum value of the gas flow reduction of $\bar{G}$ ~ 2400 into the vacuum volume from the atmosphere $\bar{P}_\Sigma \geq 10^4$ was obtained with this window for $\bar{P}_{00}$ = 80. For $\bar{P}_{00}$ = 96, $\bar{G}$ ~ 2200 and for $\bar{P}_{00}$ = 65, $\bar{G}$ ~ 1900. We note that the window design allows the working gas flow to be reduced through the high-pressure channel by somewhat reducing the pressure at its input behind the output of both channels into the working regime. In particular, experimental conditions which reduce the pressure and the flow of the working gas through the external stage of the window by 10% hardly change the established values of the parameters $\bar{P}$ and $\bar{G}$.

NOTATION

P_+, larger of the pressures separated by the window; P_-, smaller of the separated pressures; P_0, total pressure of the working gas at the input to the nozzle receiver of the window stage; G, gas flow; G_N, normalized flow; Re, Reynolds number. The indices 1 and 2 denote the number of the window stages.

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MASS TRANSFER FOR BAROMEMBRANE SEPARATION OF SOLUTIONS

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A mathematical model is obtained for transient mass transfer during the baromembrane separation of liquids for a flat channel with a semipermeable wall. Hydrated sunflower oil is used as an example to show that the theoretical and experimental time-dependences for the content of the retained material in the concentrate differ insignificantly.

Published efforts on the mathematical modeling of material separation with sempermeable membranes can be divided into two groups. In the first [1-4] the transient mass transfer problem is solved for an unmixed medium in a batch cell, which usually is used in the laboratory. In the second group [5-8], the problem is for stationary mass transfer for laminar motion of the medium in a channel with a semipermeable wall.

Moreover, in [1-4], the concentration at the separation surface (membrane—polarized layer, polarized layer—solution) is taken as a constant, while it actually depends on time. Obviously there is interest in solving the transient problem of mass transfer for an arbitrary motion of the medium (for any value of the convective diffusion coefficient) and for time-varying concentrations at the separation surface.

The separation of materials with the use of semipermeable membranes (ultrafilters, microfilters, and reverse osmosis) can be represented in the following fashion (Fig. 1):

1) The separated material is concentrated at the plane $x = R$ becuase of the removal of the permeate through the membrane;

2) The material enters a flow of concentrate through the plane $x = 0$ by convective diffusion;

3) There is molecular diffusion in the diffusion boundary layer ($0 \leq x \leq R$) of material from the membrane to the flow (concentrate) side;

4) The liquid medium (in the general case a mixture of the permeate and the separated material) filters through the membrane according to Darcy's law.

What has been said allows the problem to be described in the form

$$\frac{\partial y(x,\tau)}{\partial \tau} = D\frac{\partial^2 y(x,\tau)}{\partial x^2}\ (\tau > 0,\ 0 < x < R), \tag{1}$$

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