DISCHARGE OF A GASEOUS MEDIUM UNDER HIGH PRESSURE THROUGH A NOZZLE WITH A SMALL OPENING

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It is shown experimentally that the nature of the discharge of gaseous nitrogen under a pressure of up to 12 kbar through a nozzle with a small opening with a ratio of the length of the cylindrical section of the channel to its diameter of about unity is close to isentropic.

The study of processes of discharge of liquid and gaseous media under a pressure of 10 kbar or more has great significance both in a scientific respect and from the point of view of a whole series of possible practical applications. In particular, the question of the possibility of the achievement of isentropic discharge of a dense gas through nozzles with small openings is very important for modern experimental aerodynamics. In the experimental practice of the Institute of High-Pressure Physics, Academy of Sciences of the USSR, cases are known where the discharge of a highly compressed gas took place with a change in the gas parameters in the stream characteristic of isenthalpic gas expansion. In these experiments during the discharge of nitrogen under a pressure of ~30,000 bar through an opening 2 mm in diameter intense luminescence of the jet was observed, indicating a high thermodynamic gas temperature at a relatively low stream velocity. This shows that the process of change in the gas parameters in the stream was close to isenthalpic, accompanied by an intense increase in entropy, and the increase in gas temperature in the stream occurred as a result of the appearance of the Joule–Thomson effect. The discharge in these experiments was accomplished through an entrance channel having a cylindrical shape with a ratio of length to diameter equal to ~10. A similar effect can be observed during discharge through a channel having the shape of a Laval nozzle with small enough sizes of the critical cross section and in the presence of a cylindrical section of a certain length near the critical part of the contour. We attempted to study the possibility of achieving isentropic discharge of a highly compressed gas through nozzles with openings of no more than 0.1 mm.

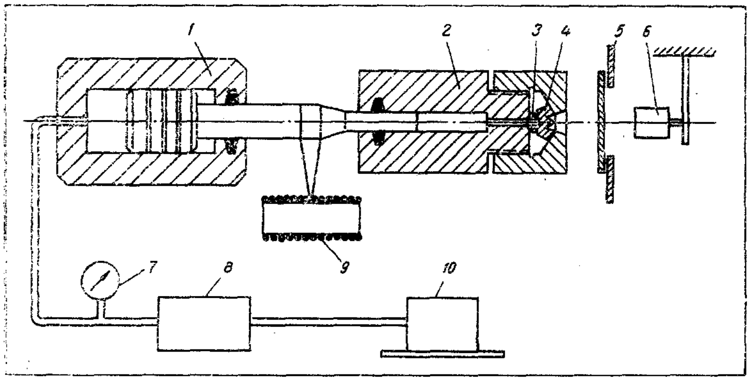

Fig. 1. Diagram of apparatus: 1) large cylinder of booster; 2) small cylinder of booster; 3) nozzle; 4) breaking membrane; 5) gate; 6) impulsometer; 7) manometer. 8) reservoir; 9) slide wire; 10) compressor.

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TABLE 1. Dependence of Breaking Pressure of Membranes on Their Dimensions

A, mm	P, kbar
1,0	4,2— 6,5
1,5	6,1— 8,7
2,0	8,3—10,7
2,5	10,0—12,3

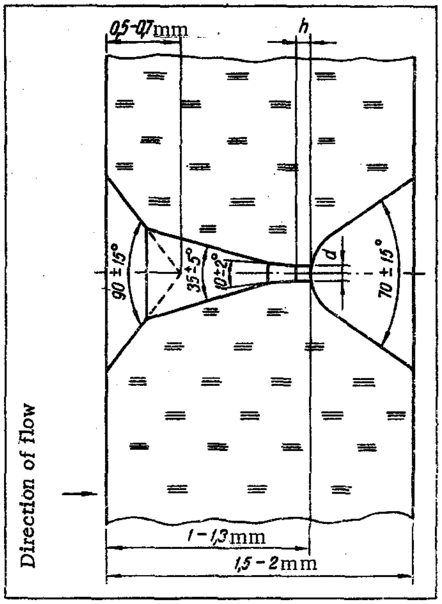

Fig. 2. Configuration of inner channel of nozzle. d = (0.02-1.2) mm; h/d = 0.75.

The apparatus shown schematically in Fig. 1 was used to achieve the discharge of gaseous nitrogen under a pressure of from 4 to 12 kbar. This apparatus differs little fundamentally from that described earlier [1] for the study of discharge processes in liquids. Its main element is a pressure booster with the supply of compressed air to the large cylinder from a reservoir of the required capacity.

The main difference between this system and the previous one consists in the fact that the breaking membrane device designed to start the operation of the apparatus, which in the case of liquid discharge was located in front of the air entrance to the large booster cylinder, is mounted in a gasdynamic assembly immediately behind the nozzle at the exit of the working gas from the small cylinder. This change in the system is connected with the need to provide complete airtightness for the cavity of the small cylinder after the creation of the preliminary pressure of the working gas and the rapid opening of the exit opening at the starting time.

In order that the average duration of gas discharge would be about one second in the range of pressures in front of the nozzle studied, the diameter of the exit opening in the nozzle was decreased to 0.06 mm and the volume of the small cylinder of the booster was increased to 3.14 cm^3 through a corresponding increase in the piston travel. Moreover, in the case of gas discharge some additional increase in the duration of the

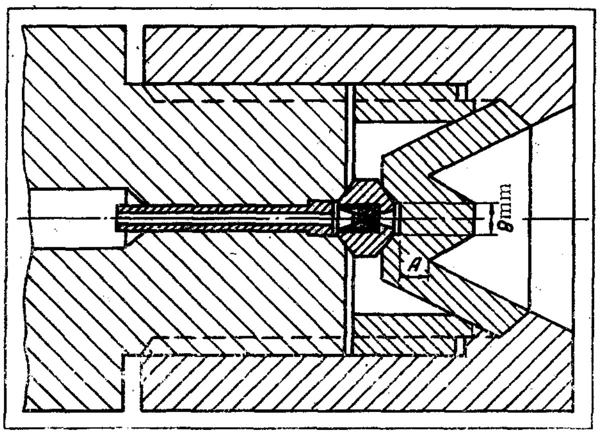

Fig. 3

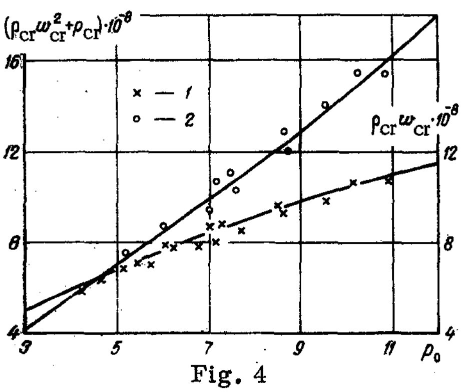

Fig. 4

Fig. 3. System of mounting nozzle and breaking membrane.

Fig. 4. Comparison of experimental and calculated values of gas flow rate (1) and total flow impulse of jet (2) in critical cross section of nozzle. $(\rho_{cr}w_{cr}^2 + p_{cr}) \cdot 10^{-8}$, N/m^2; $\rho_{cr}w_{cr} \cdot 10^{-8}$, g/sec · m^2; p_0, kbar.

discharge occurs because of the more intense decrease in gas density in the critical cross section of the stream compared with the corresponding density of the liquid.

Diamond dies of industrial manufacture for the drawing of small diameter wire (GOST 627-60T) and nozzles made of a metal—ceramic solid alloy (VK-6, VK-8, and others) were used as the nozzles for the gas discharge.

The channel configuration of the diamond dies used is shown in Fig. 2. It is obvious that from a hydrodynamic point of view the channel configuration of a diamond die has several advantages compared with the configuration of a steel nozzle which is used in experiments on liquid discharge. The diamond channel has a smoother convergent section, the ratio of the length of the cylindrical section of the channel to its diameter is $h/d = 0.75$, all the elements of the channel have a regular geometrical shape, and its surface is prepared according to the highest class of precision and purity. The industry presently manufactures diamond dies with a diameter of from 0.02 to 1.20 mm for the narrowest (calibrating) part.

No significant change in the shape and dimensions of the openings was detected during the entire duration of gas discharge of several minutes as a result of the periodic monitoring of possible erosion of wall material of the nozzle openings during their prolonged exploitation. The monitoring was done with an instrumental microscope with measurement errors of no more than 0.001 mm.

The nozzles were mounted at the exit from the small cylinder of the booster using special steel bushings. The die or nozzle was mounted in the bushing with a special centering device with a radial gap, after which epoxy resin was poured into the gap, which after hardening assured a fully airtight bond at high gas pressures.

The bushing assembly containing the nozzle as well as the molded breaking membrane assembly at the exit from the small cylinder of the booster are shown in Fig. 3. Airtightness in all the joints was assured by the high value of the pressing force produced by the appropriate fastening elements. The molded breaking membranes, whose configuration is seen in Fig. 3, were made from ÉI 654 steel. The approximate experimental dependence of the pressure at which the rupture of the membrane occurs on one of its characteristic dimensions is shown in Table 1.

The sealing of the small piston of the booster used in the discharge of a viscous liquid proved to be quite unsuitable for work on gaseous nitrogen. In connection with this the instrument was fitted with a specially developed seal for the small piston [2] which provided complete airtightness of the cylinder filled with gas at pressures up to 20 kbar and a comparatively low frictional force which was 10-25% of the axial force.

The pumping of compressed air at a pressure of 500 bar into the reservoir from which the large cylinder of the booster was supplied was done with a compressor constructed by M. F. Posolin [3]. This compressor consists of a booster whose large cylinder is additionally fitted with a slide-valve gas-distributing mechanism providing a reciprocating motion of the piston, while the small cylinder has a corresponding valve mechanism.

To create the preliminary pressure in the small cylinder of the booster we employed the effect of an increase in pressure during an isochoric change in the aggregate state of the working medium. For this purpose liquid nitrogen was poured into the small cylinder of the booster, the body of which was preliminarily cooled to the boiling temperature of liquid nitrogen, after which the cavity of the small cylinder was hermetically closed by the mounting of the nozzle with the bushing and membrane and tightening of the mounting elements under a layer of liquid nitrogen using a special accessory. As a result of the evaporation of nitrogen in the closed volume during its heating to room temperature the pressure in the small cylinder of the booster was raised to ~2.8 kbar.

The subsequent raising of the gas pressure to the required value was accomplished by additional compression by the piston in the small cylinder. For this purpose after the small cylinder was heated to room temperature compressed air was pumped into the large cylinder of the booster and the reservoir communicating with it, as a result of which the booster piston was displaced producing the additional compression of the working gas in the small cylinder of the booster to the required pressure.

When the required gas pressure in the small cylinder of the booster was reached the membrane blocking the cylinder was ruptured. The discharge of gas was accompanied by a corresponding displacement of the booster piston, providing practically constant gas pressure in front of the nozzle during the entire discharge period. The volume of the reservoir which communicated with the large cylinder was chosen in such a way that the decrease in gas pressure in front of the nozzle was no more than 5-8%.

Two gas-dynamic parameters were measured in the process of the discharge of gaseous nitrogen under high pressure through the nozzle: the flow rate of the gas and the total flow impulse of the jet in the critical cross section of the nozzle.

To measure the flow rate of the gas the instrument was equipped with a device permitting the recording of the law of motion of the piston. This device consisted of a slide wire whose coil was mounted rigidly parallel to the axis of the booster while the contact sliding along the coil was fastened rigidly to the piston. The variation in the current in the slide wire circuit was recorded on a loop oscillograph. The gas flow rate was determined from the measured displacement velocity and the area of the piston cross section and from experimental data on the density of nitrogen at the corresponding pressures and room temperature [4].

The gas pressure in front of the nozzle during the discharge was determined from the results of pressure measurements in the large cylinder of the booster with allowance for experimental data on the frictional force in the packings [2].

The results of the experiments show that just as in the case of the discharge of a liquid, after a brief period of accelerating motion the booster pistons moved with a constant velocity and without noticeable oscillations during the discharge of the gas, which indicates the equilibrium of the forces applied to them and the constancy of the pressure of the working gas in front of the nozzle during the discharge.

A specially developed "impulsometer" instrument [5], consisting of a gas sampler with a radial gas entrance suspended on a tensometric balance, was used to measure the total flow impulse of the gas jets obtained on the apparatus. To protect the instrument from the impact of the core of the membrane which flies at a high velocity an assembly was used which contained a movable gate attached to the membrane core with a tight wire. The gate opened automatically under the effect of a spring after the core struck it as a result of the release of the wire.

The results of the experimental determination of the gas flow rate and total flow impulse of the jet in the critical cross section of the nozzle are presented in Fig. 4. The experimental data are presented in the form of points on the diagrams of the dependence on the gas pressure p_0 in front of the nozzle of the flow rate $\rho_{cr}w_{cr}$ and impulse $\rho_{cr}w_{cr}^2 + p_{cr}$ per unit area of the critical cross section of the stream. The corresponding curves obtained by calculation are plotted on the diagrams for comparison.

The calculated curves were obtained by the graph method using an I—S diagram constructed from experimental data on the thermodynamic properties of nitrogen in the range of pressures of from 600 bar to 12 kbar and temperatures of from 180 to 300 °K [6, 7, 8]. To determine the thermodynamic parameters of the gas in the critical cross section of the stream and at the critical speed of sound during isentropic discharge auxiliary dependences of the current density ρw on the enthalpy of the gas were constructed for a series of isentropic cross sections of the diagram. Here the velocity w of the stream was determined from the corresponding drop in enthalpy as $w = \sqrt{2g\Delta I}$. As is known, during isentropic discharge the current density ρw always has a maximum in the critical cross section of the nozzle, hence the critical parameters of the stream were determined from the coordinates of the maximum points on the current density curves. As the results of a comparative analysis show, the values of the critical speed of sound in the gas obtained by this method agree well with the experimental data [9, 10].

It follows from the data presented in Fig. 4 that the results of the theoretical and experimental determinations of the flow rate of the gas through a unit area of the critical cross section of the nozzle, expressed by the value $\rho_{cr}w_{cr}$, agree well with one another. The same conclusion follows with respect to the total flow impulse in the critical cross section of the nozzle per unit area of the stream cross section, $\rho_{cr}w_{cr}^2 + p_{cr}$.

The calculated values of the two complexes of gas-dynamic values considered are determined from fully reliable experimental data on the thermodynamic properties of the working gas in the appropriate ranges of the parameters using assumptions concerning the isentropic law of variation in the gas parameters during the discharge.

Thus, the good agreement of the calculated and experimental values of the two independent complexes of gas-dynamic values in the critical cross section of the stream indicates that the law of variation in the gas parameters during discharge through a nozzle remains close to isentropic with an increase in the gas pressure in front of the nozzle to ~12 kbar and a decrease in the diameter of the critical cross section of the nozzle down to 0.06 mm.

NOTATION

h, d	are the length and diameter of cylindrical section of nozzle channel;
$\rho_{cr}, w_{cr}, p_{cr}$	are the density, velocity, and pressure of gas in critical cross section of nozzle;
p_0	is the gas pressure in small cylinder of booster;
I	is the enthalpy of gas;
S	is the entropy of gas;
ρ, w	are the density and velocity of gas in arbitrary section of stream;
g	is the acceleration of free fall.

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