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SUPERSONIC GAS EJECTORS

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INTRODUCTION

The currently employed gas ejectors with cylindrical mixing chambers and divergent diffusers have a great drawback; it is impossible to attain in them a very great pressure rise in one stage. Thus, for instance, in a stage of an ejector with subsonic nozzles having an ejection rate near zero and very great pressure ratios of high- and low-pressure gases one obtains a compression ratio of 4–5:1. In an ejector with a supersonic nozzle for the high-pressure gas in analogous conditions, one-stage compression ratio can be as great as 15–20:1. Ejectors with convergent conical mixing chambers have a somewhat greater compression ratio but a considerable increase of the compression presently is being achieved by reverting to multistage schemes, which entail a complication of construction and an increase of ejector dimensions.

We have proposed some new schemes of ejector stages with great static-pressure gradients in the high-pressure gas jet in the initial portion of the mixing chamber and with a feed of the low-pressure gas into a low-pressure region. In such stages having great pressure ratios of high- and low-pressure gases and an ejection rate near zero, a considerably greater compression can be attained mainly owing to reduction of losses, associated with breaking of the supersonic stream of the gas mixture in the diffuser. It is explained by the fact that, with equal ratios of pressures, the mean velocity of the high-pressure supersonic gas jet (and therefore of the gas mixture) in such ejectors reaches considerably lower values than in conventional ejectors.

In this paper we investigate limiting characteristics of a simple scheme of a new type ejector. A static-pressure gradient in the high-pressure gas jet in this stage is formed as a result of a sudden expansion of the jet in the initial portion of the mixing chamber. In addition, there is a brief description of the ejector stage, in which a static-pressure gradient in the high-pressure gas jet is formed by giving the walls of the nozzles and the initial portion of the mixing chamber a certain curvature.

LIMITING CALCULATED CHARACTERISTICS OF AN EJECTOR WITH A SUDDEN EXPANSION OF THE HIGH-PRESSURE GAS JET

A scheme of the ejector in question with a sudden expansion of the high pressure gas jet is shown in Fig. 1. The ejector consists of nozzles for high- and low-pressure gases, a cylindrical mixing chamber and a divergent diffuser. The low-pressure nozzle to the left of the section *a-a* is convergent and between the sections *a-a* and *I-I* is cylindrical. The high-pressure nozzle may be either supersonic (dashed lines) or subsonic. The outlet section of the low-pressure nozzle is situated in the mixing chamber at a distance l_c from the inlet. The outlet section of the high-pressure nozzle coincides with the outlet section of the mixing chamber. Areas of the outlet sections of the high- and low-pressure nozzle and the mixing chamber we will call f_a', f_I, and F respectively. The area of the critical section of the high-pressure nozzle will be designated as f_{cr}'.

At the design regime the high-pressure gas flows from the nozzle either with sonic or supersonic velocity depending on nozzle configuration. In the initial portion of the mixing chamber a sudden expansion of the high-pressure gas jet takes place with a boundary separating the jet from a stall region (Fig. 1) reaching the walls of the mixing chamber. The static pressure in the region of the sudden expansion of the jet changes abruptly both over the width and the length of the mixing chamber, reaching its minimum at the ejector axis at a certain distance from the nozzle. In order to get a maximum compression the outlet section of the low-pressure nozzle must be placed in the region of minimum pressure.

The velocity of the low-pressure nozzle outlet can vary from zero to a critical value, depending on the ratio of stagnation pressures P_0' and P_0 of high- and low-pressure gases. In the outlet section of the mixing chamber the supersonic stream of the gas mixture becomes subsonic in a normal shock wave.

In the divergent diffuser there will be a slowing down of the subsonic stream.

It is evident that the compression in this ejector with other conditions remaining the same will be larger, the smaller are the ejection ratio, the exit area of the low-pressure nozzle f_I and the reduced velocity of low-pressure gas $\lambda_1 = W_1/a_*$ (W = stream velocity, a_* = critical velocity). Therefore, for an evaluation of limiting values of the ejector compression ratio we take $K = 0$, $f_1' = 0$ and $\lambda_1 = 0$. Besides, we assume that pressure in the outlet section of

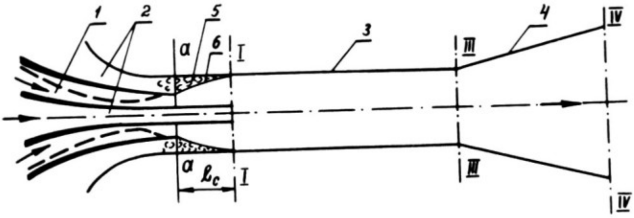

Fig. 1. Scheme of the ejector with sudden expansion of the high-pressure gas jet: (1) high-pressure nozzle, (2) low-pressure nozzle, (3) mixing chamber, (4) diffuser, (5) stall region, (6) jet boundary.

the low-pressure nozzle is equal to the minimum static pressure in the zone of sudden expansion of the high-pressure gas jet. Actually the pressure in the low-pressure nozzle at $K = 0$ must be somewhat less owing to low base pressure.

With these assumptions, the ejector compression $\mathcal{E}$, equal to the ratio of stagnation pressures of the gas mixture at the diffuser outlet P_{04} and of the low-pressure gas P_0, is given by

$$\mathcal{E} = \frac{P_{04}}{P_0} = \frac{P_{04}}{P_{\min}'} = \frac{P_0'}{P_{\min}'} \cdot \frac{q(\lambda_3')}{q(1/\lambda_3')}\nu_d \tag{1}$$

where $\nu_d = P_{04}/P_{03}$ = pressure-recovery coefficient in the diffuser

λ_3' = reduced velocity of supersonic stream of gas mixture at the end of the mixing chamber

$q(\lambda) = \lambda[I - (x - I/x + I)\,\lambda^2]\,(I/x - I)$ = reduced air flow

$x = C_p/C_v$ = ratio of specific heats

The reduced velocity λ_3' in Eq. (1) with a sufficient accuracy for practice can be taken as follows:

$$q(\lambda_3') = q'(I)F_{cr}' \tag{2}$$

In the case of a conventional type ejector scheme, low-pressure gas is fed into the mixing chamber through a peripheral annular nozzle (Fig. 1).

The maximum compression in this case is attained in the previously described regime as well. Stagnation pressure of low-pressure gas is equal to the pressure in the stall region ($P_0 = P_{3.0}$) and the compression is defined by

$$\mathcal{E}_{3.0} = \frac{P_{04}}{P_{3.0}} = \frac{P_0'}{P_{3.0}}\frac{q(\lambda_3')}{q(1/\lambda_3')}\,\nu_d \tag{3}$$

where the reduced velocity λ_3' is given by Eq. (2). The pressures $P_{\min}'$ and $P_{3.0}$ were derived by calculating the flow in the region of sudden expansion of the high-pressure gas jet. The known method of characteristics was used.

In Fig. 2 are shown calculated curves of limiting compression ratios in the new ejector with sudden expansion of the high-pressure gas jet against the pressure ratio P_0'/P_0 for a series of values of reduced velocity $\lambda\alpha'$ at the nozzle outlet. There are also curves f_{cr}' = constant and limiting values $\mathcal{E}(P_0'/P)$ for an optimum ejector with a supersonic high-pressure nozzle and for a conventional ejector with convergent nozzles. It is seen that, in the whole range of pressure ratios the new ejector has considerably greater limiting pressure ratios than the optimum ejector and the ejector with convergent nozzles.

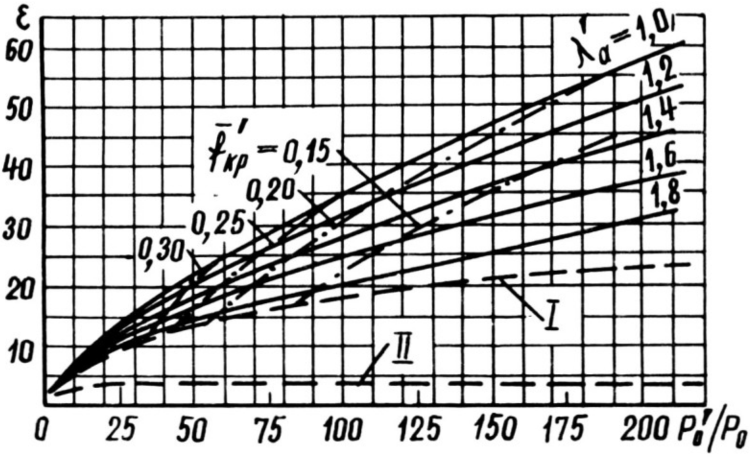

Fig. 2. Curves of the limiting pressure-rise ratio in the ejector with sudden expansion of the high-pressure gas jet against the ratio of pressures: (1) optimum conventional ejector, (2) ejector with convergent nozzles.

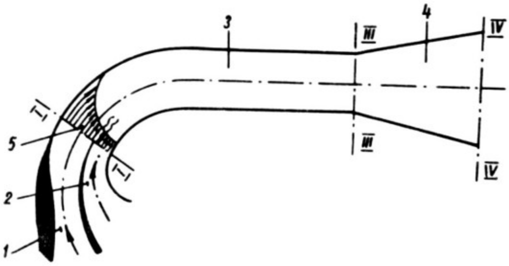

Fig. 3. Scheme of the ejector with curvilinear axis: (1) high-pressure supersonic nozzle, (2) convergent low-pressure nozzle, (3) mixing chamber, (4) diffuser, (5) static-pressure distribution.

THE EJECTOR WITH CURVILINEAR AXIS

The scheme of the ejector with a curvilinear axis is presented by Fig. 3.

The ejector consists of a high-pressure supersonic nozzle, a low-pressure subsonic nozzle, a mixing chamber and a diffuser. The axes of the nozzle and of the initial portion of the mixing chamber are curved, the low-pressure gas being fed into at the convex wall of the mixing chamber.

The curvature of the walls of the nozzles and of the mixing chamber entails a building up of static-pressure gradients, directed from the convex wall to the concave one. In connection with this for securing the ejection process there is no necessity to expand all the high-pressure gas to a pressure less than the stagnation pressure of the low-pressure gas as is done in conventional ejectors. Only a small part of the high-pressure gas undergoes a strong expansion near a boundary in contact with the low-pressure gas jet.

In Fig. 4 a calculated plot (1) of limiting compression in the ejector with a curvilinear axis in dependence on compression ratio P_0'/P_0 is indicated. As in the case of the ejector with sudden expansion, the calculations were performed for

$K = 0$, $f_1 = 0$, $\lambda_1 = 0$ and $P_0 = P_{\min}'$. Besides, it was assumed that the velocity of the high-pressure gas follows a relation wR = constant, beginning from $w_1' = a'$ at the concave surface and extending to a certain value w_2', defined by the ratio P_0'/P at the convex surface. On the same figure theoretical limiting pressure ratio (2) in the optimum ejector with the high-pressure supersonic nozzle is shown. Comparing the curves it is seen that limiting compressions in the ejector with a curvilinear axis at $K = 0$ are considerably greater than limiting pressure ratios in the optimum ejector.

RESULTS OF AN EXPERIMENTAL INVESTIGATION OF THE EJECTOR WITH SUDDEN EXPANSION OF THE HIGH-PRESSURE GAS JET

The scheme of the investigated ejector is indicated in Fig. 5. The ejector consists of a convergent nozzle (1), a cylindrical tube (2), an annular nozzle (3), a mixing chamber (4), a settling chamber (5), and a divergent diffuser.

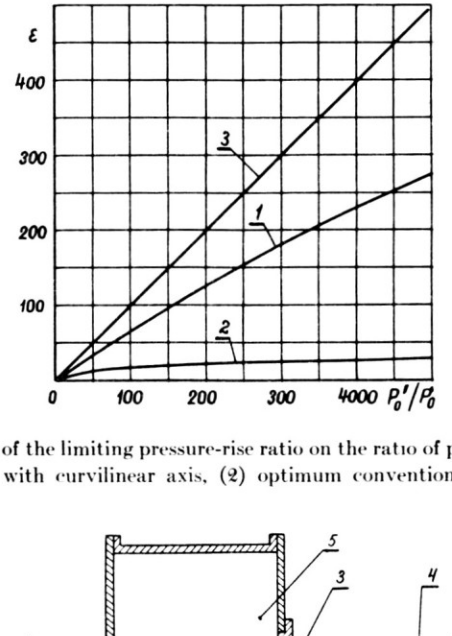

Fig. 4. Dependence of the limiting pressure-rise ratio on the ratio of pressures for different ejectors: (1) ejector with curvilinear axis, (2) optimum conventional ejector, (3) ideal ejector.

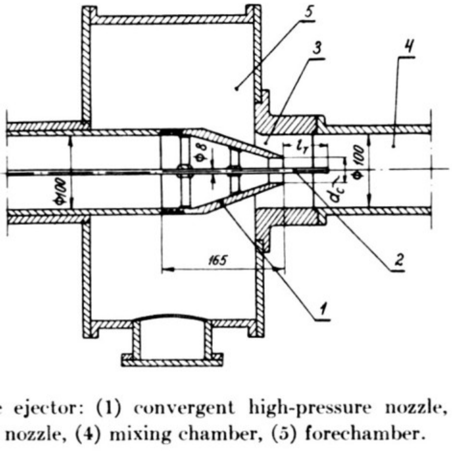

Fig. 5. Scheme of the ejector: (1) convergent high-pressure nozzle, (2) central tube, (3) annular nozzle, (4) mixing chamber, (5) forechamber.

The convergent nozzle, through which the high-pressure gas was being fed into the mixing chamber, was made in three versions with different diameters of the outlet sections.

The central tube was positioned at the ejector axis, and a possibility of displacement of its open end within a range up to 185 mm from the nozzle outlet was given.

In the investigated ejector the low-pressure gas can be fed into the mixing chamber either through the peripheral annular nozzle (conventional scheme), through the central tube (scheme of an ejector with sudden expansion), or simultaneously through the central tube and the peripheral annular nozzle.

The purpose of the present investigation was a comparison of limiting characteristics of the ejector with sudden expansion of the high-pressure gas jet with those of the conventional ejector. Therefore, air supply lines to the settling chamber and to the central tube were closed. In this case both ejectors worked in a regime of zero ejection rate.

The relation between the compression $\mathcal{E}$ and P_0'/P_0 at the regime of zero ejection ratio in the conventional ejector with the nozzle $NI[d_c = (\bar{d}_c/D) = 55]$ is shown in Fig. 6. The vertical portion of the curve $\mathcal{E}\ (P_0'/P_0)$ corresponds to the critical working regimes of the ejector, when the final shock wave is situated in the diverging portion of the diffuser or at the end of the mixing chamber. To the maximum pressure of the high-pressure gas $P_0' = 5.6$ atm corresponds a lower point at the vertical portion of the characteristic ($\mathcal{E} = 3.1$, $P_0'/P_0 = 17.5$). With a decrease of the pressure P_0' down to 3.1 atm the compression of the ejector rises up to $\mathcal{E} = 5.6$ and the ratio of pressures remains constant ($P_0'/P_0 = 17.5$). With a further decrease of the pressure P_0' the compression and the ratio of pressures decreases linearly.

The relation between the compression ratio $\mathcal{E}_T$ in the ejector with nozzle No. 1 ($\bar{d}_c = 0.55$) and the ratio P_0'/P_{0T} for several distances from the tube end to the outlet section of the nozzle $[\bar{l}_T = (l_T/D)]$ is given by Fig. 7. The throttle characteristics were measured for two methods of starting the ejector to the design regime: (1) without regulation and (2) with regulation. In the former case (continuous lines) the tube had been placed beforehand in the necessary position and after this the ejector flow was raised to the critical regime. In the

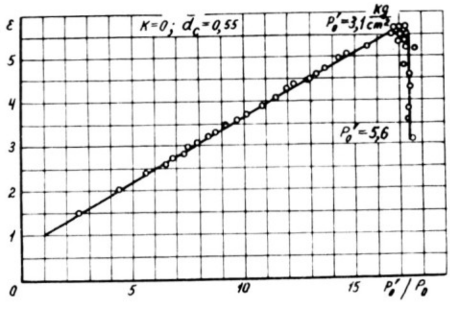

Fig. 6. Dependence of the limiting pressure-rise ratio in the conventional ejector with convergent nozzles on the ratio of pressures ($\bar{d}_c = .55$).

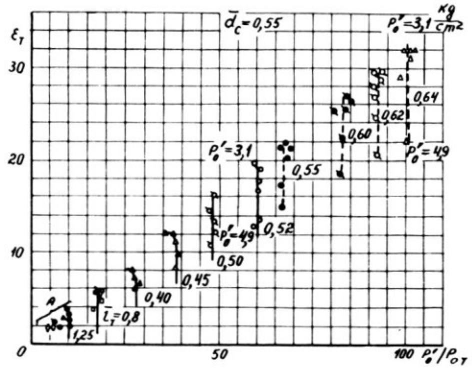

Fig. 7. Dependence of the limiting pressure-rise ratio in the ejector with central tube on the ratio of pressures ($\bar{d}_c = .55$); solid line, without starting regulation; dashed line, with starting regulation.

latter case (dashed lines) raising to the critical regime was effected at $\bar{l}_T = 0$, when the tube end had been placed in the outlet section of the nozzle, and after starting of the ejector the tube was moved into the necessary position. In both cases an optimum position of the tube was determined, corresponding to a minimum pressure in it ($P_{\min T}$).

Let us consider at first throttle characteristics of the ejector without starting regulation. The best results in this case were obtained at $\bar{l}_T = 0.52$. At a pressure of the high-pressure gas $P_0' = 4.9$ atm and with the tube in optimum position, the pressure ratio in the ejector was 12.5 and the ratio of pressures was 0.64. With a decreasing of the pressure P_0' down to 3.1 atm, the pressure ratio increases up to 19.5 and the ratio of pressure remains unaltered. With a further decrease of the pressure of the high-pressure gas the pressure in the tube abruptly rises and therefore $\mathcal{E}_T$ and P_0'/P_0 decreases suddenly. In Fig. 7 points corresponding to these regimes at all values of $\bar{l}_T$, fall in the region *A*. A reverse picture is observed with gradual increasing of the pressure P_0'.

In this case the quantities $\mathcal{E}_T$ and P_0'/P_0 increase suddenly from values corresponding to the region *A* to values corresponding to the tops of vertical branches of the characteristics. Thence the characteristics of the ejector with the central tube, having no starting regulation, have reversible discontinuities.

The origin of such discontinuities in the characteristics is explained by changing the position and form of the compression shocks, arising in the initial portion of the mixing chamber, in connection with a penetration of disturbances from the diffuser into the peripheral region.

From Fig. 7 it follows that by using the starting regulation it is possible to increase substantially the limiting pressure ratio in the ejector being considered. Thus at the optimum position of the tube ($\bar{l}_T = 0.64$) the compression ratio $\mathcal{E}_T = 32$ was obtained, and the ratio of pressures $P_0'/P_0 = 100$. It will be remembered that in experiments with a conventional ejector the compression ratio $\mathcal{E} = 5.6$ was obtained, and the ratio of pressures $P_0'/P_0 = 17.5$.

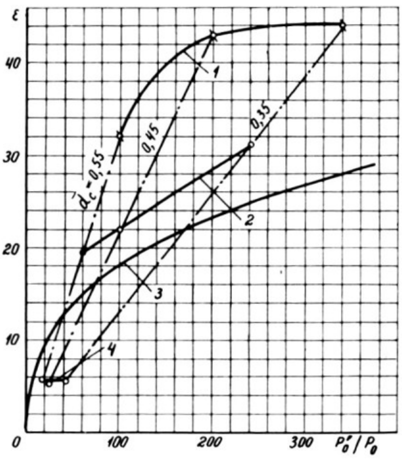

Fig. 8. Dependence of the limiting pressure-rise ratios on the ratio of pressures for ejectors of different schemes: (1) and (2) ejector with sudden expansion of the high-pressure gas jet with and without starting regulation, (3) optimum conventional ejector; conventional ejector with convergent nozzles.

It is worth noting that the discontinuity in the throttle characteristics, measured with the starting regulation at $\bar{l}_T$ lying in the range from 0.52 to 0.64, is irreversible.

The effect of the starting regulation can be explained by the possibility of different kinds of shock waves forming as a result of the boundary layer on the central tube.

Fig. 8 shows the experimental relation between the limiting compression and the ratio of pressures of the high- and low-pressure gases for the conventional ejector with convergent nozzles (4) and for the new ejector with (2) and without (3) starting regulation. For the sake of comparison, theoretical values $\varepsilon\ (P_0'/P_0)$ for the optimum ejector (1) with the high-pressure supersonic nozzle at zero ejection rate are given on the same figure. It is to be seen that the limiting pressure ratios in the new ejector are considerably higher than the limiting pressure ratios in the ejector with convergent nozzles and in the optimum conventional ejector.