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GAS EJECTOR AS A PRESSURE STABILIZER AT THE INLET TO COMPRESSOR POWER INSTALLATION

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Optimum supersonic gas ejector design procedure for application as pressure stabilizer at the inlet to compressor power installation is developed.

Introduction

Gas ejectors find wide application in different areas of technique, especially in the aviation, gas, chemical and vacuum industries. Possibility to have as a result of gas jets interaction a mixture with average pressure higher, than pressure of environment where the mixture acts, attracts scientific workers and stimulates further research.

The main advantage of the gas ejector as a jet compressor is the absence of details which move. Technical and technological simplicity, possibility to use it in aggressive and high-temperature environments become crucial far the gas ejector as a jet amplifier of pressure at an inlet to power machine compressors.

Analysis of research and publications

The first scientific publications on studying the process of mixing two jets of incompressible environments appeared in the 1920s [1; 2]. A possibility of practical ejector application caused much interest in scientific research circles.

In the USSR a group of scientists was engaged in research of different ejectors leaded by of professor K.N.Baulin [3]. Ejector calculations were carried out with the use of the techniques based on the principles of interaction of turbulent jets of a liquid on the basis of the semi-empirical theory of turbulent jets of G.N. Abramovich [4].

The most authentic method of calculation of gas ejector with the cylindrical mixing chamber at any pressure differences has been created by academician S.A.Khristianovich [5]. However, the method of calculation did not take into account possible changes of the speed of low-pressure gas at the inlet to the mixing chamber.

In 1947 in his work [6] B.M.Kiselyov or completed the technique for the case of mixing gases with different braking temperatures and offered simple solution formulas for gas ejectors with the help of gas dynamic functions.

1948 discovery by CAGI scientific workers M.D. Millionschinkov and G.M.Rjabinkov of the critical ejector operating modes has essentially contributed to S.A.Khristianovich's basic research. So, areas of mixing jets parameters at the inlet to the ejector which cannot be realized in the set mixing chamber are found out, therefore basic equations of ejection are not enough.

In work [7] it has been shown, that there is no need to make full calculation of turbulent jets mixing for ejector calculation. For this purpose it is enough to take into account only gas dynamic interaction of jets acting in the mixing chamber. In terms of critical mode, equality of static pressure of mixing jets in «lock-out» section and equality of Mach number to one for low-pressure jets in this section were accepted.

Right after that the theory of limiting modes by Taganov-Medgirov [8] with a linear structure high-pressure stream has been offered to a jet in «lock-out» section of the mixing chamber which took into account the equation of linear momentum.

The theory of supersonic ejector with a cylindrical mixing chamber by J.M.Vasiliev [9] proved to be most successful. In it the equation of movement quantity value with uniform fields of speeds in «lock-out» section of every stream was carried out, and in to static pressure distribution there was a break.

During experimental researches axisymmetric ejector with central nozzle of high-pressure gas corresponding specifications were proposed.

The theory of gas ejector limiting modes with regard to the influence of viscosity has been developed by Chow and Addy [10] and became the completion of the theory of optimum gas ejector of classical structure.

Optimum ejector provides a suction setting the task of set amount of low-pressure gas with the minimal consumption of high-pressure gas. Determination of optimum ejector is a search of geometrical parameters in the optimal mode of its operation and a mode of the minimal pressure at an inlet. Under the set conditions the optimum ejector has the greatest possible capacity.

Therefore all searches have been aimed at determination of conditions of an optimal gas ejector. As has been proved, in the presence of direct jump of condensation in the mixing chamber that ejector is optimal which works in critical modes under any pressure at an inlet.

Unfortunately, the carried out scientific works were aimed at improvement of gas ejectors, which could work at negative gradients of pressure. Influence of additional gradient of pressure due to the work of the power machine on a stream of a gases mixture in the mixing chamber ejector is under investigated.

Therefore creation of a design procedure of optimum ejector as the jet compressor for the power machine is actual and necessary.

The purpose of research

The purpose of research is the search of geometrical sizes of optimum gas ejector under the conditions of significant reduction of pressure at an inlet to the compressor power machine.

The analysis of supersonic gas ejector operating modes and ejection equations

For the analysis of supersonic gas ejector operating modes we shall consider the basic diagram and design sections which are shown in fig. 1.

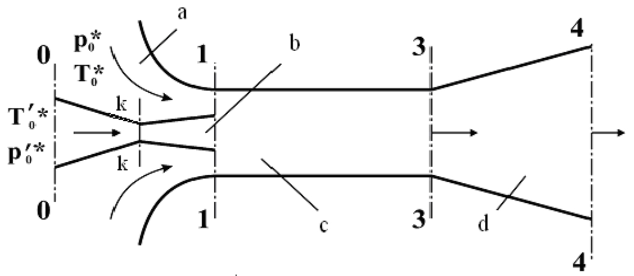

Fig. 1. The basic diagram of supersonic ejector:
a – low-pressure gas nozzle; *b* – high-pressure gas nozzle; *c* – the mixing chamber; *d* – run-out;
0–0 – an inlet into supersonic nozzle; *1–1* – an inlet to the mixing chamber; *3–3* – an output from the mixing chamber; *4–4* – an output from the run-out; *k–k* – critical section of the supersonic nozzle

The diagram stipulates inflow of low pressure gas from the gas network to the gas ejector through subsonic nozzle-*a*. High-pressure gas from the accumulator moves at a big speed through the pressure regulator of pressure into the supersonic nozzle-*b* and in the mixing chamber-*c* interacts with low-pressure gas. Mixture of gases gets out through runout-*d.* Section *2–2* is conditional and it is considered as the moment of realization of equality of static pressure of jets in the mixing chamber.

In fig. 2 there is a diagram of flow at equality of static pressure of mixing jets in initial nozzle section and with a jump of condensation in the mixing chamber. It is intended for supersonic nozzle sizes determination.

At significant pressure drop at an inlet into compressor installation, diagrams of flow are realized which are given in fig. 3.

With such diagram the supersonic nozzle works in under expansion modes, the static pressure along the nozzle decreases, and the speed increases with transition to supersonic flow. In the mixing chamber the supersonic jet extends, compressing in the subsonic, their speeds increase. At further reduction of pressure near the inlet section *2–2* moves away from the initial nozzle section more and more. At the minimal pressure at the inlet there occurs a critical mode of the mixing chamber «lock-on».

All modern supersonic ejector design procedures are based on the solution of the basic ejection equations which are the result of the joint solution of mass conservation equations, energy and movement quality value for inlet and output sections of mixing chambers in view of Mayer equations and status.

Thus one-dimensional flow of ideal gases is considered, neglecting heat exchange and friction between jets of mixing gases and ejector design.

A complete system of the ejection equations at mixing gases with different physical performances and in view of factors of pressure restoration in the nozzles ($\gamma 1 = p1^*/p0^*$ and $\gamma 1 = p1'^*/p0'^*$) and in the runout ($\gamma 4 = p4^*/p3^*$) looks as follows:

$$\varepsilon = \frac{\chi'}{\chi_3}\sqrt{\frac{(\chi_3+1)(\chi_3-1)(K/\sigma+1)(K+1)}{(\chi'+1)(\chi'-1)}}\,\frac{\gamma_4\gamma_1'\sigma q(\lambda_1')}{(\alpha+1)q(\lambda_3)}; \quad (1)$$

$$\frac{\chi'}{\chi}\sqrt{\frac{(\chi+1)(\chi-1)}{(\chi'+1)(\chi'-1)}}\,\frac{K}{\sqrt{\vartheta}} = \frac{\alpha\gamma_1 q(\lambda_1')}{\sigma\gamma_1' q(\lambda_1')};$$

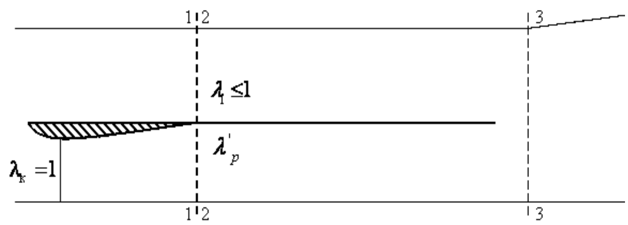

Fig. 2. The diagram of flow at equality of static pressure of mixing jets in initial nozzle section

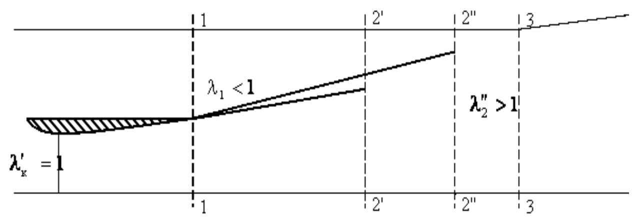

Fig. 3. Diagrams of flow including condensation jump in the gas ejector mixing chamber and equality of static pressure of mixing jets in section *2–2*

$$z(\lambda_3)=\frac{\chi_3}{\chi'}\sqrt{\frac{(\chi'+1)(\chi'-1)}{(\chi_3+1)(\chi_3-1)}}\times$$

$$\times\frac{\dfrac{\chi'}{\chi}\sqrt{\dfrac{(\chi+1)(\chi-1)}{(\chi'+1)(\chi'-1)}}\dfrac{K}{\sqrt{\vartheta}}z(\lambda_1)+z(\lambda'_1)}{\sqrt{(K/\vartheta+1)(K+1)}}; \qquad (2)$$

$$\chi_3=\frac{\chi(K+c'_p/c_p)}{K+\chi c'_p/\chi' c_p};$$

$$\tau=\frac{K+\vartheta}{K+1},$$

where $\varepsilon = p_3{}^*/p_0{}^*$, $\sigma = p_0'/p_0{}^*$, $\vartheta = i_0'^*/ i_0{}^*$, $\tau = i_3/i_0{}^*$ are a degree of pressure increase, characteristic relative pressure, the characteristic ratio of enthalpy, a degree of gas ejector enthalpy increase, respectively; c_p, c'_p, χ, χ', χ_3 are specific heat capacities and parameters of an adiabatic curve of low-pressure and high-pressure jets of gas, respectively; K, α – are the ejection factor and the basic run-out geometrical size; $q(\lambda_1)$, $q(\lambda')$, $q(\lambda_3)$, $z(\lambda_1)$, $z(\lambda')$, $z(\lambda_3)$ are gas dynamic functions of low-pressure, highpressure gas jets and of mix, respectively.

Equation (2) at

$z(\lambda_{3max}) \geq z(\lambda_3) \geq 2$,

where

$\lambda_{\max}=\sqrt{(\chi+1)/(\chi-1)}$,

gives two values of the resulting speed at the inlet section of the mixing chamber.

The first value ($\lambda_3>1$) corresponds to the supersonic flow of gases, and the second ($\lambda_3<1$) – to subsonic. The value $z(\lambda_3)=2$ corresponds to the sound flow of mixture at the inlet section of the mixing chamber.

Equation (1) with the set parameters of mixing jets at the nozzle section at supersonic flow at the output section of the mixing chamber also gives two values of a degree of pressure increase: ε' – corresponds to supersonic flow of a mix of gases, ε''– to subsonic. These values are connected by the ratio

$\varepsilon''=\varepsilon' q(\lambda_3)/q(1/\lambda_3)$.

So, subsonic flow arises from supersonic due to a direct jump of condensation. In a general case of mixing up jets with different physical performances the system of five ejection equations has sixteen variables.

For its solution, it is necessary to add five more equations which depend on nozzle and run-out operating conditions as well as ejector operating mode. For this purpose it is necessary to know processes of jets interaction on the initial site of the mixing chamber.

In case of mixing gases of the same nature in a gas ejector, with identical enthalpy, under condition $i_0'^*/i_0{}^*$ the system of the equations is simplified to the kind:

$$\varepsilon=\frac{K+1}{\alpha+1}\frac{\gamma_4\gamma'_1\sigma q(\lambda'_1)}{q(\lambda_3)}; \qquad (3)$$

$$K=\frac{\alpha\gamma_1 q(\lambda'_1)}{\sigma\gamma'_1 q(\lambda'_1)}; \qquad (4)$$

$$z(\lambda_3)=\frac{Kz(\lambda_1)+z(\lambda'_1)}{K+1}; \qquad (5)$$

$$\chi=\chi'=\chi_3; \qquad \tau=1. \qquad (6)$$

As the speed in the supersonic nozzle inlet section λ'_p does not change at overcritical pressure differences for a gas ejector with the set geometry equation (3) and (4) may be presented as complexes of parameters which do not change at the change of pressure in a gas network:

$$\left(\frac{\varepsilon}{\gamma_4\sigma}\right)_i\frac{1}{K_i+1}=\frac{1}{\alpha+1}\frac{\gamma'_1 q(\lambda'_p)}{q(\lambda_3)}=\text{const}; \qquad (7)$$

$$\left(\frac{K_i\sigma_i}{\gamma_i q(\lambda_{1i})}\right)=\frac{\alpha}{\gamma'_1 q(\lambda'_p)}=\text{const}. \qquad (8)$$

The joint solution (7) and (8) looks like:

$$\left(\frac{\varepsilon}{\gamma_4}\right)\frac{K_i}{K_i+1}\frac{1}{\gamma_1 q(\lambda_1)}=\frac{\alpha}{\alpha+1}\frac{1}{q(\lambda_3)}=\text{const}. \qquad (9)$$

According to (7), dependence of ejection factor K on the basic power parameter of gas ejector with constant productivity as the complex

$(\varepsilon/\gamma_4\sigma)_i=p_4/p_i'^*$

is a straight line which crosses an axis $(\varepsilon/\gamma_4\sigma)_i$ at the limiting value of power parameter, $(\varepsilon/\gamma_4\sigma)_{ãð}$ thus K=0. The straight line inclination depends on the interrelation between the speed values λ'_p, λ_3 and the basic geometrical parameter. Therefore the problem of searching geometrical sizes of an optimum gas ejector consists in determining this interrelation in the starting mode of gas ejector with realization of $(\varepsilon/\gamma_4)_{\max}$ and the mode of expected minimal pressure with realization of $(\varepsilon/\gamma_4)_{\max}$. So,

$$\left(\frac{\varepsilon}{\gamma_4\sigma}\right)_{ãð}=\frac{1}{\alpha+1}\frac{\gamma'_1 q(\lambda'_p)}{q(\lambda_3)}. \qquad (10)$$

At realization of the critical mode of flow in the subsonic nozzle at the moment of gas ejector start the maximal value of ejection factor K_{max} will be determined under the formula:

$$\left(\frac{\varepsilon}{\gamma_4}\right)_{\min}\frac{K_{\max}}{K_{\max}+1}=\frac{\alpha}{\alpha+1}\frac{1}{q(\lambda_3)}.$$

Expression (8) enables to find necessary gas dynamic regulation of supersonic gas ejector due to corresponding increase of pressure at the inlet in supersonic nozzle for realization G_4=const.

To determine the maximal value of ejection factor K_{max} with realization $(\varepsilon/\gamma_4)_{min}$ for the mode of the supersonic gas ejector start we shall consider the basic ejection equations (3)–(6) of "ejector-run-out" system through a minimum function (3) search at constant values σ, K, γ_1, γ'_1, γ_4 and physical parametrs of mixing gases, having taken advantage of the known dependence of Khristianovich [6] as:

$$\varsigma = \frac{2}{\chi M_3^2}\left(\delta - \frac{\delta^2}{2}\right) \text{ or } \varsigma = \frac{\chi+1}{\chi}\left(\delta - \frac{\delta^2}{2}\right), \quad (11)$$

де $\delta = 1 - \gamma_4$.

So, the equation (3) can be considered as:

$$\varepsilon = \frac{K+1}{\alpha+1}\frac{\gamma_4\gamma_1'\sigma q(\lambda_1')}{q(\lambda_3)}(1 - \varsigma\frac{\chi}{\chi+1}\lambda_3^2). \quad (12)$$

Let's make use of the method of Lagrange uncertain multipliers for search of stationary points. Stationary points of function (12) are there where all Lagrange partial derivative functions are equal to zero:

$$\lambda' = 1, \quad (13)$$

$$\lambda_1 = 1, \quad (14)$$

$$\frac{\varepsilon p(\lambda_3)}{\sigma\gamma_1'\gamma_4 p(\lambda_1')} = \frac{\left(1 + \frac{\varsigma\chi}{\chi+1}\lambda_3^2\right)\left(\frac{1+\lambda_3^2}{1-\lambda_3^2}\right)}{1 - \frac{\varsigma\chi}{\chi+1}\lambda_3^2}; \quad (15)$$

$$\sigma\gamma_1' p(\lambda_1') - \gamma_1 p(\lambda_1) = 0. \quad (16)$$

Let's analyze stationary points in order to determine the condition of gas ejector optimal and the initial data of its use. Realization of condition (13) is possible only in the subsonic narrowing nozzle of high-pressure gas which is to work in the critical mode. According to [10], the optimum gas ejector with the narrowing nozzle of the high-pressure jet is less powerful (by 2–3 times) than the gas ejector with the expanding nozzle.

Performance of condition (13) is possible at realization of the flow diagram which is given in fig. 2. It corresponds to the case of mixing jets with equal static pressure in output nozzle sections, i.e. at meeting condition (15) simultaneously.

The of consumption low-pressure gas G_3 in this case, will be maximal, and the degree of pressure increase in the gas ejector will be determined by condition (16). Further, on the degree of pressure increase will increase proportionally to pressure reduction at the gas ejector inlet.

The use of such a flow diagram enables to determine parameters of the subsonic nozzle during its critical mode operation and the minimal productivity of compressor unit. At pressure reduction at the compressor unit inlet the pressure difference at the subsonic nozzle will decrease, owing to pressure increase at the supersonic nozzle output.

From the equation of gas consumption in sections *1–1*, *3–3* and *4–4* (fig. 1) at the set parameters of gas in the gas network and design productivity of the compressor unit there are such equations of interrelation between gas ejector geometrical parameters and flow speed at the mixing chamber output:

$$F = \frac{Q\gamma_4}{mR\sqrt{T_0^*}\,q(\lambda_3)};$$

$$f_1 = F\frac{\alpha}{\alpha+1};$$

$$f_1' = F\frac{1}{\alpha+1},$$

where F, f_1, f'_1, are the area of the mixing chamber of low-pressure and high-pressure nozzles; Q – is productivity of a compressor unit.

The common solution of the equations (14)–(16) enables to define characteristic attitudes of full pressure ε_{min} and σ_{min} in the starting mode of the supersonic gas ejector whose values depend only on the jets speed in the gas ejector mixing chamber. So,

$$\left(\frac{\varepsilon}{\gamma_4}\right)_{min} = \frac{p(1)}{p(\lambda_3)}\frac{1 + \frac{\zeta\chi}{\chi+1}\lambda_3^2\left(\frac{1+\lambda_3^2}{1-\lambda_3^2}\right)}{1 - \frac{\zeta\chi}{\chi+1}\lambda_3^2}.$$

The value $(\varepsilon/\gamma_4)_{min}$ enables to be determine the value of pressure at the compressor unit input p_i at the moment of the supersonic gas ejector start which will not change during pressure reduction at the inlet p_i in view of the losses in the run-out.

The expected value $(\varepsilon/\gamma_4)_{max}$ is the major in calculating gas ejector geometrical parameters and should be set. It characterizes the flow critical mode with the minimal value of ejection factor K_{min}. With the known speed at the subsonic nozzle output in such a mode λ_{1min} and the known value of ejection factor K_{min} reaches the maximal value of $\lambda_{1min} = \lambda_3$ and is easily determined with the help of complex (9). Using complexes (7) and (8) it is possible to calculate the necessary value σ_{max} in this mode.

The critical mode at $\sigma = \sigma_{max}$ arises in the case when the minimal pressure upon at the inlet to the compressor unit will decrease to the value of static pressure at the output from the high-pressure nozzle.

The theory of basic critical mode by Vasiliev [7] determines the interrelation between speeds in section *1–1* and *2–2* of the ejector as follows:

$$q(\lambda'_2) = \frac{q(\lambda'_1)}{\alpha+1}\frac{1}{1-\dfrac{\alpha}{\alpha+1}\dfrac{q(\lambda_1)}{q(\lambda_2)}}; \quad K = \frac{z(\lambda'_2)-z(\lambda'_1)}{z(\lambda_1)-z(\lambda'_2)}.$$

The mode of mixing chamber lock-on arises at $\sigma=\sigma_{гр}$, when between section *1–1* and *2–2* the expansion of the supersonic jet fills in all mixing chambers section. In section *2–2* there is a direct jump of condensation with transition to subsonic flow at the speed λ_3. So, parameters of a supersonic stream before a jump should meet corresponding conditions which are determined with the help of known parities:

$$\lambda_3\lambda'_2 = 1;$$

$$p'_3{}^* = p_2'^*\frac{q(\lambda_2')}{q(1/\lambda_2')} = \gamma'_1 p_1'^*\frac{q(1/\lambda_3)}{q(\lambda_3)};$$

$$\left(\frac{\varepsilon}{\gamma_4\sigma}\right)_{гр} = \mu\left(\frac{q}{\lambda_3}\right). \qquad (17)$$

Common solution of equations (10) and (17) allows for establishing the dependence of a gas ejector basic geometrical parameter from speed values of high-pressure stream in the supersonic nozzle and stream mixes in the mixing chamber as:

$$\alpha = \frac{\gamma' q(\lambda'_p)}{q(1/\lambda_3)} - 1.$$

From the equation of gas consumption in sections *k–k* and *1–1* of the high-pressure nozzle, in sections *3–3* and *4–4* of the gas ejector run-out at the maximal productivity of a compressor unit *Q*, this can be provided the gas ejector. At a direct jump of condensation there are such equations of interrelation between the gas ejector geometrical parameters and the flow speed at the mixing chamber output:

$$f_k = \frac{Q}{mR\sqrt{T_0^*}}\frac{\gamma'_k\gamma_4}{\mu(\lambda_3)},$$

where γ'_k is the factor of preservation of full pressure in the expanding part of the supersonic nozzle.

Thus, the certain interrelation of all geometrical sizes of the optimum ejector with the value of the stream speed of gas mixture in the final section of the mixing chamber λ_3 which the losses of full pressure in the run-out and which through equation (11) is connected with the value of the calculated speed in the high-pressure nozzle λ_3, depends on.

Conclusion

The technique offered in the article allows for determining geometrical sizes of the supersonic gas ejector which can be used as a pressure stabilizer at the inlet to the compressor power installation by the known parameters of its productivity and possible values of pressure reduction at the inlet.

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Газовий ежектор як стабілізатор тиску на вході в компресорну енергетичну установку

Розроблено методику розрахунку оптимального надзвукового газового ежектора для використання як стабілізатора тиску на вході в компресорну енергетичну установку.

Н.С. Кулик, К.И. Капитанчук, П.И. Греков, С.П. Онищенко

Газовый эжектор как стабилизатор давления на входе в компрессорную энергетическую установку

Разработана методика расчета оптимального сверхзвукового газового эжектора для применения в качестве стабилизатора давления на входе в компрессорную энергетическую установку.