CONTOURING OF GAS-DYNAMIC CONTOUR OF THE CHAMBER

Main assembly of the rocket engine creating a thrust, is the combustion chamber. On fig. 1 the scheme of chamber LPRE, working on bipropellant is adduced. It will consist of the combustion chamber 1 and a jet nozzle 2, structurally representing a single whole. The combustion chamber has the mixing head 3, which serves for a components supply of fuel (an oxidizing agent and fuel) in the chamber.

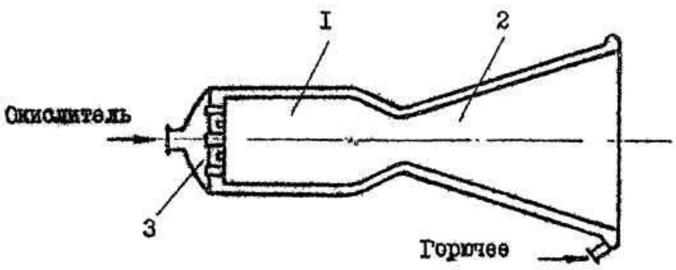

Fig. 1. The scheme of LPRE chamber

Fuel after inflaming burns at high (till 15-20 МПа and more) pressure, thus is formed gaseous combustion products with temperature 3000-4500 K, which effuse to the ambient space through the nozzle. On length of the nozzle the temperature and pressure of them decrease, and the velocity increases, passing through a sound velocity in minimum (critical) cross-section of the nozzle and reaching 2700-4500 m\s on a shear of the nozzle.

The more second flow rate of a propulsive mass and exhaust velocity on a shear of the nozzle, the more thrust created by the chamber. Specific impulse $I_{уп}$ created by the chamber by activity in vacuum, it is possible to present as follows;

$$I_{уп} = \beta K_{тп} \quad . \qquad (1)$$

Here:

$$I_{уп} = \frac{P_{п}}{\dot{m}};$$

$$\beta = \frac{p_к F_{кр}}{\dot{m}};$$

$$K_{тп} = \frac{P_п}{p_к F_{кр}}.$$

$P_п$ - a thrust of the combustion chamber in vacuum;

$\dot{m}$ - the mass second flow rate of a propulsive mass;

$p_к$ - combustion-chamber pressure;

$F_{кр}$ - the area of minimum (critical) cross-section.

The flow rate complex characterizes itself efficiency of transformation of chemical energy of fuel in thermal energy combustion products, i.e. quality of activity of the combustion chamber.

Thrust coefficient $K_{тп}$ characterizes efficiency of transformation of thermal energy of a propulsive mass in a kinetic energy of a jet stream, i.e. quality of activity of the nozzle.

Main characteristics of a propulsion system depend on quality of activity of the combustion chamber and the nozzle, their profitability - specific impulse and its weight.

For build-up of gas-dynamic profile of the engine chamber at known input datas it is necessary to execute thermal calculation of an engine, to select the form, to calculate a volume and geometry of the combustion chamber, and also a profile of a jet nozzle. Chamber pressures and on a shear of the nozzle, and also ambient pressure; vacuum thrust or on a sea level, propellant components and their ratio are input datas.

1. SELECTION OF THE VOLUME AND GEOMETRY OF THE COMBUSTION CHAMBER

Process of transformation of fuel in combustion products will consist of an atomization - subdivisions of fuel on drops and initial their allocation in a volume of the combustion chamber; a warm-up and evaporation of drops; mixings of vapor of fuel and an oxidizing agent; chemical reactions - naturally process of combustion. Listed processes happen in time. Their duration depends on sizes of the combustion chamber. The volume of the combustion chamber should supply such fuel residence time that complete combustion of fuel was implemented, and losses of specific impulse were minimum.

The volume of combustion chamber V_K is its volume from the mixing head down to critical cross-section of the nozzle.

Because of complexity of working process, the theoretical method of calculation of a required volume of the combustion chamber is not created yet. For definition of this volume experimental parameters and semiempirical relations are used.

1.1. Definition of the combustion chamber on a conditional residence time

Residence time this time necessary for completion of elementary processes in the combustion chamber and incineration of fuel with necessary completeness;

$$\tau_{п} = \frac{V_{к}}{\dot{m}\upsilon_{ср}} \quad , \qquad (2)$$

where:

$$\upsilon_{ср} = \frac{1}{\tau_{п}} \int_{0}^{\tau_{п}} \upsilon d\tau$$

mean specific volume of combustion products in the chamber during residence time.

To estimate a time on completion of each elementary process difficultly. Also it is difficult to determine the mean specific volume $\upsilon_{ср}$, therefore is used parameter which refers to as a conditional residence time;

$$\tau_{усл} = \frac{V_к}{\dot{m}\upsilon_к}, \qquad (3)$$

where

$$\upsilon_к = \frac{R_к T_к}{p_к} \text{ -}$$

computational specific volume of combustion products.

from (3) computational expression for scoping of the combustion chamber receives:

$$V_к = \frac{\dot{m} R_к T_к}{p_к} \tau_{усл}.$$

For the chamber with the constant area, $F_{кр}$ the relation $\frac{\dot{m}}{p_к}$ is practically constant. If to neglect effect of pressure on $R_к T_к$ (pressure $p_к$ does not influence processes of transformation) it is possible to define, that value of $\tau_{усл}$ depends on a kind of used fuel, quality of a mixing and a volume of the chamber.

For used in LPRE fuels $\tau_{усл}$ lays within the limits 0,0015÷0,005c and it is determined experimentally. At large chamber pressures $\tau_{усл}$ is closer to a floor level. In engines with afterburning generator gas where one of propellant components usually completely evaporates in the gas generator, recommended values in 1,3÷1,8 time smaller, than for the engine without afterburning.

1.2. Scoping of the combustion chamber on reduced length.

Приведенной (или характеристической) длиной камеры сгорания называется величина

Reduced (or characteristic) length of a combustion-chamber is:

$$L_{пр} = \frac{V_к}{F_{кр}} \tag{4}$$

From here the design formula for scoping of the chamber looks like

$$V_к = L_{пр} F_{кр} \tag{5}$$

It is easy to show, that reduced length and a conditional residence time are proportional parameters:

$$L_{пр} = A_n \sqrt{R_к T_к} \tau_{усл}$$

Values $L_{пр}$ depend in main on a kind of used fuel and are determined experimentally.

In tab. 1 values $L_{пр}$ for some fuels of LPRE, known of the literature are given.

Fuel	Kerosene + oxygen	Hydrogen + oxygen	Ammonia + a fluorine	NSDH + nitric acid (N_2O_4)	Kerosene + nitric acid (N_2O_4)
$L_{пр}$, м	1,5 – 2,0	0,25 – 0,5	1,0 – 1,5	1,5 – 2,0	1,25 – 1,6

For the same fuel the value $L_{пр}$ changes in a broad band since experimental data have been obtained at different combustion-chamber pressures and different organization of process of a mixing.

1.3. Determination of the combustion chamber volume on a liter thrust

The liter thrust is a thrust referred to one liter of a volume of the combustion chamber;

$$P_{л} = \frac{P}{V_{к}}. \qquad (6)$$

From here the design formula looks like

$$V_{к} = \frac{P}{P_{л}}. \qquad (7)$$

It is possible to show, that the liter thrust is not the characteristic only combustion chambers since the long of a thrust removed from the nozzle enters in its) expression also. Its values depend on a kind of fuel and combustion-chamber pressure. For existing LPRE the liter thrust varies within wide range of limits from 1 up to 100 кN/l. Iт hampers for used of this parameter for determination of the combustion chamber volume without additional data, for example on engine - analog.

It is necessary to mark, that the pressure buildup and improvement of organization of a mixing and combustion processes result in decreasing of a necessary residence time, i.e., to decreasing of required values $\tau_{усл}$ and $L_{пр}$. Thus, with perfecting of LPRE and a pressure increasing in the chamber the trend to decreasing of a volume of the combustion chamber occurs.

1.4. Definition of cross-sectional area of the combustion chamber

After scoping of the combustion chamber, it is necessary to select its form and to calculate ratio between its main geometrical sizes. Now for majority LPRE the combustion chamber of the cylindrical form is used.

It speaks its design both technological simplicity and a capability together with the flat mixing head to ensure a random distribution of fuel in cross section of the

Large effect on parameters of the combustion chamber renders parameter $\overline{F}_к = \frac{F_к}{F_{кр}}$, which is termed as the dimensionless area of the combustion chamber. The actual combustion chamber has a finite value of $\overline{F}_к$, and process in it represents a flow of a compressible gas in a cylindrical pipe with a heating. Under these requirements there is a thermal resistance result in losses of an impact pressure in the chamber and a drop of its thrust and specific impulse.

It is possible to show, that for combustion chambers with $\overline{F}_к$>3 and more large expansion ratio, that is peculiar to the modern LPRE, effect of thermal resistance can be neglected. The value $\overline{F}_к$=3 determines boundary of geometry of so-called isobaric combustion chambers.

Существенным ограничением при выборе малых значений $\overline{F}_к$ является сложность организации процесса смесеобразования при высоких значениях расходонапряженности $q = \frac{\dot{m}}{F_к}$. Для современных камер сгорания расходонапряженность с ростом давления в камере увеличивается. Определение расходонапряженности рекомендуется производить по следующей эмпирической формуле :

Essential limitation by selection of small values of $\overline{F}_к$ is complexity of organization of process of a mixing at high values of flow rate intensity $q = \frac{\dot{m}}{F_к}$. For the modern combustion chambers flow rate intensity with increasing of chamber pressure increas. Definition flow rate intensity is recommended to be made under following empirical formula:

$$q = (0{,}8 \div 1{,}3)p_к \text{, g/sm}^2\text{s.} \qquad (8)$$

Here $p_к$ undertakes in ата.(absolute atmosphere)

On value of flow rate intensity cross-sectional area of the combustion chamber is usually determined

$$F_к = \frac{\dot{m}}{q}, \qquad (9)$$

and then fulfillment of a requirement of isobaric is checked up. For isobaric chambers fulfillment of a requirement $\overline{F}_к > 3$ is necessary.

2. CONSTRUCTION OF THE CONTOUR OF THE ROUND AXISYMMETRICAL NOZZLE ON THE BASIS OF FREELY DILATING FLOW

Considering a field of flow in the Laval nozzle (fig. 2), it is possible to divide it into some reference areas. On an axis of the nozzle two reference points are located: O - center of the nozzle, in which the velocity is equal to a sound velocity, and A - a point in which computed speed of flow is reached.

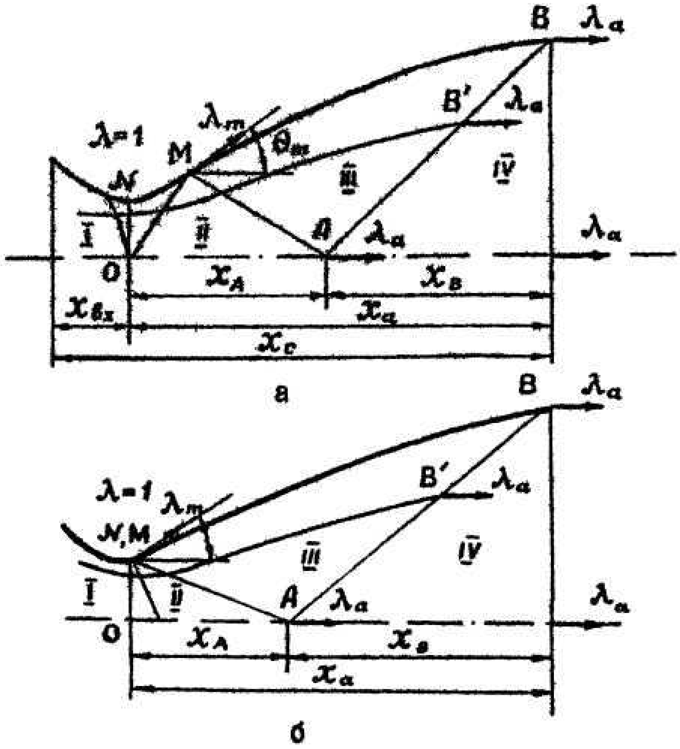

Fig. 2. The reference areas of flow in the Laval nozzle

Area I - area of a subsonic flow, up to a surface of transition through a sound velocity.

Area II - from surfaces of transition through a sound velocity up to characteristic AM, going upstream from a point A. In this area flow velocity and an angle of inclination of velocity vector to an axis of the nozzle at motion along a streamline is continuously increased. The angle of inclination reaches maximum value in the points located on characteristic AM. This area is termed as area of preliminary expansion.

The area III is located between two characteristics of different sets of AM and AB. In this area flow velocity prolongs to be increased. The angle of inclination of velocity vector to an axis of the nozzle after the characteristic of AM starts to decrease, reaching minimum value on characteristic AB. This area terms as area of equalization of a flow.

In area IV, located behind characteristic AB on an output, flow which is the reference for the given nozzle is implemented. In most cases at calculation initial or base nozzles the requirement of obtaining of the uniform and parallel flow or the homogeneous flow at output is.

In the capacity of a nozzle contour it is possible to accept a streamline (more truly, the surface of a current), called as a limiting. Limiting streamline at a curvilinear surface of transition through a sound velocity (fig. 2á) is a line which passes through a point of M of interception of characteristics of different sets:

- The characteristic of second set AM, which has been upstream from a point A, lying on an axis, where the velocity of flow reaches computational value for the given nozzle;

- Characteristics of the first set an OM, draw DOWNSTREAM from a point O on an axis where the velocity reaches a sound velocity.

If the surface of transition through a sound velocity is flat (fig. 2b), the characteristic of the first set the OM coincides a surface of transition, and a point of M of interception of characteristics the OM and AM displaces in a plane of critical cross-section. The limiting STREAMLINE receives with a fracture - an angle in critical cross-section.

The scheme of such nozzle has received a title of the nozzle with an angular point or an angular input.

At designing of nuzzles with a fracture of a streamline in critical cross-section on a segment of preliminary expansion it used flow which receives at the free expansion of an axisymmetrical jet with plane surface of transition through a sound velocity.

At streamlining of an angular point there is a Prandtl-Mayer flow: in a fan of rarefaction waves - the characteristics leaving an angular point, the flow is dilated, increasing speed from $\lambda = 1$ up to $\lambda > 1$, and at the same time turns on a an angle $\theta > 0$.

From a numberless set of characteristics of a fan of rarefaction waves one characteristic of AM (fig. 3), passing through a point A on an axis of flow in which computed speed is reached is selected $\lambda_{a.}$

On the other hand, in a point of M on this characteristic the velocity reaches value of λ_m, and a critical angle of its deviation - θ_m is. This characteristic for the given nozzle will be boundary between zones of preliminary expansion and equalization.

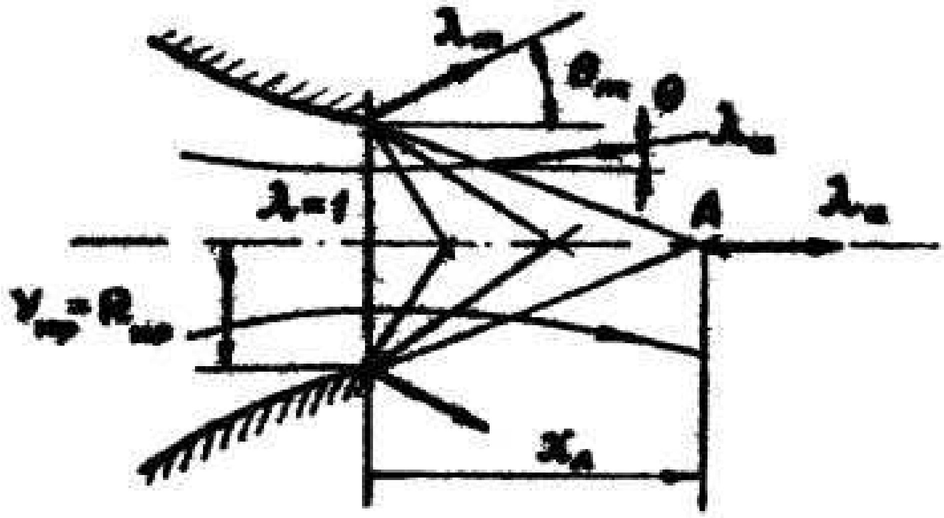

Fig. 3 the Scheme of the free dilating flow

The nozzle with completely parallel and uniform expiration is not the most expedient. The best will be the nozzle with some degree of parallel misalignment on an exit, at which the least losses and weight receive. Nozzles with the given parallel misalignment of the expiration can be built as follows.

To calculate and build the nozzle with completely parallel expiration, but with obviously large output cross-section, than it is necessary. Such nozzle we shall term initial or base. Then this initial nozzle mast be cut off in cross-section where tangent to a contour forms with an axis of the nozzle an angle, equal to a selected angle on a shear.

It is natural, that at such construction the initial or base nozzle should be selected so that the truncated nozzle, except for the given angle of parallel misalignment on a shear, would have also the given diameter of a shear. For this purpose it is necessary to have the set calculated and built beforehand base nozzles.

For acceleration of construction of a contour of a supersonic part a nozzle usually beforehand calculate coordinates of contours of series initial nozzles. Then represent them in a kind convenient for practical use. For example, there are reference tables of coordinates of contours of a series of base nozzles, calculated by a characteristics method. These nozzles differ computed speed λ_a and a polytropic exponent of expansion - k.

Under these tables, having a preset value of non-parallelism on an exit and shear relative diameter, it is possible to find the acceptable base nozzle and, having its co-ordinates to construct the necessary truncated nozzle.

The contour of the acceptable nozzle with sufficient accuracy for practice use can be constructed and more simple way, using approximation by its parabola, or other polynomial function.

As the quantitative characteristic of the nozzle length is relative length L_e, equal to the sum of its lengths of subsonic and supersonic parts:

$$\bar{x}_c = \bar{x}_{вх} + \bar{x}_a ,$$

where

$$\bar{x}_{вх} = x_{вх} / y_{кр} ,$$

$$\bar{x}_a = x_a / y_{кр} \text{ -}$$

relative lengths entrance and output (supersonic) nozzle parts.

From two part lengths of nozzle $\bar{x}_{вх}$ and $\bar{x}_a$ the length of a supersonic part as the most bulky has major importance, especially at large expansion ratios.

2.1 Contouring of an entrance (subsonic) part

At contouring of the nozzle with an angular input for a site of preliminary expansion, free expansion of an axis-symmetrical stream with a flat surface of transition in sound speed is used. For obtaining of a flat transitive surface entrance part of the nozzle should be appropriate amount contoured. To these conditions satisfies a contour of an entrance part of the nozzle constructed by a known formula of Vitoshinsky

$$y = y_{кр}\left(\sqrt{1-\left[1-\left(\frac{y_{кр}}{R_к}\right)^2\right]\left[1-\left(\frac{x}{x_{вх}}\right)^2\right]^2 \Big/ \left[1+\frac{1}{3}\left(\frac{x}{x_{вх}}\right)^2\right]^3}\right)^{-1} , \qquad (10)$$

And length of entrance part $x_{вх} \geq 2R_к$, where $R_к$ - combustion chamber radius.

The nozzle constructed by this formula differs by very smooth, stretched form of critical section area (fig. 4).

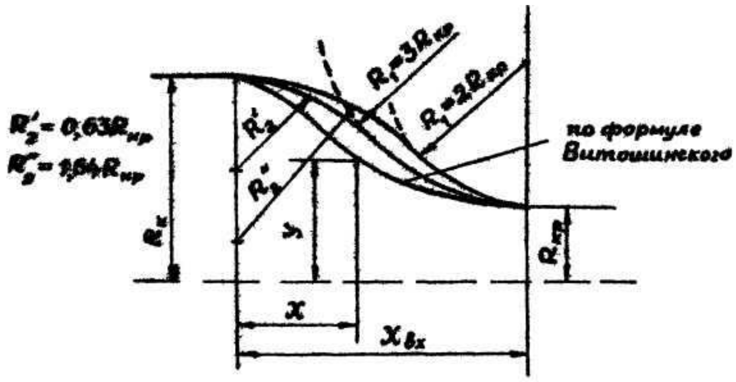

Fig. 4.Construction of a structure of an entrance of the nozzle

The contour executed on an arc in radius R_1=3$R_{кр}$ is close enough to Vitoshinsky’s contour. In practice, proceeding from technological and constructive reasons, and also necessities of the nozzle entrance part length reduction, often nozzle entrance part is contoured by an arc of some smaller radius: R_1=2$R_{кр}$, That is the basic condition for a flat transition surface execution in sound speed.

2.2. An order of the the nozzle approximate calculation with an angular input

I. To the set flow expansion ratio $\varepsilon = \frac{p_{co}}{p_a}$ and to a known parameter of a polytrack *n* we can determine a computational Mach number on a nozzle shear:

$$M_a = \sqrt{\frac{2}{n-1}\left[\left(\frac{p_{co}}{p_a}\right)^{\frac{n-1}{n}} - 1\right]} \qquad (11)$$

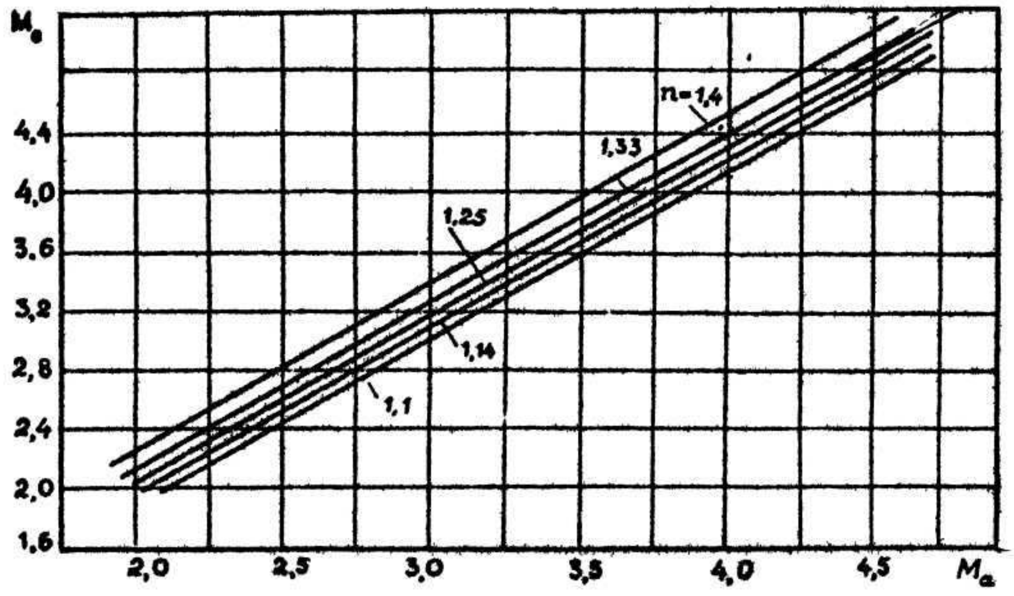

Fig. 5 Relation M_o of a Mach number on a nozzle shear

2. We determine under the drawing (fig. 5.) some Mach number M_0, corresponding to the initial nozzle.

3. By the value M_0 we calculate gas-dynamics function T

$$T = \left(\frac{1 + \frac{n-1}{2} M_0^2}{\frac{n+1}{2}} \right)^{\frac{n+1}{2(n-1)}} . \qquad (12)$$

4. For given Mach number M_a and a polytrack parameter *n* under the fig. 6 $\overline{L}_{соп} = f(M_a, n)$ we found optimum length of the nozzle.

$$L_{соп} = \overline{L}_{соп} 2R_{кр} . \qquad (13)$$

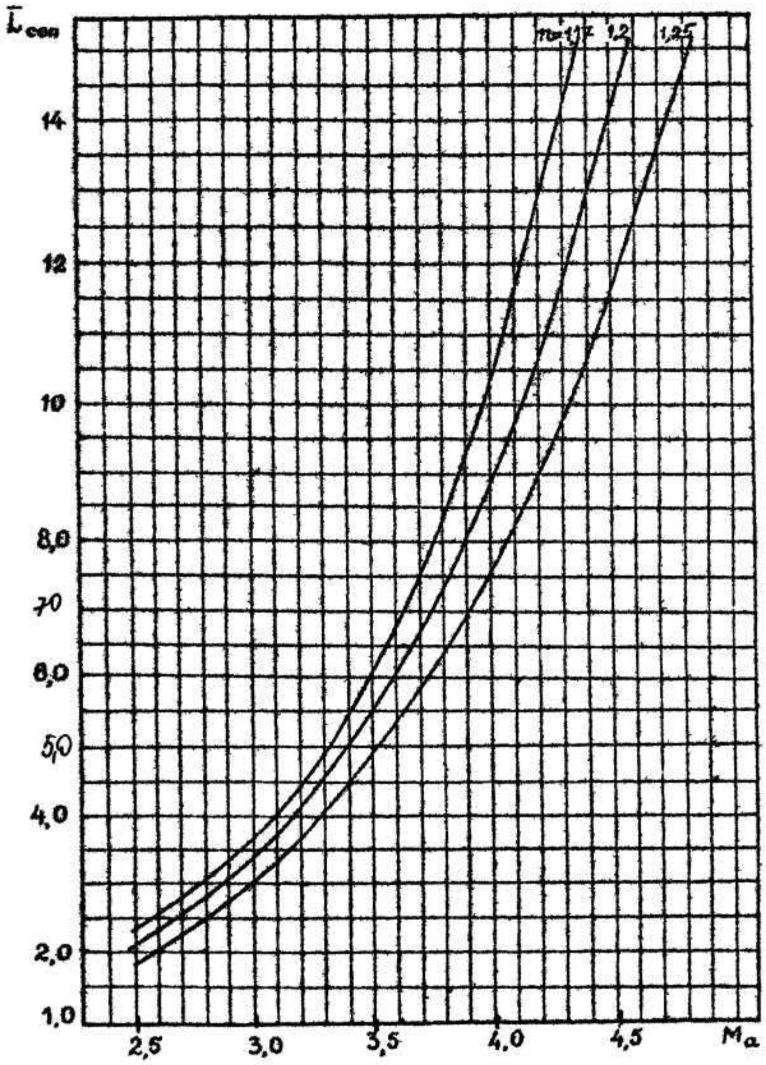

Fig. 6. Relation of the nozzle optimum length to Mach number on a shear

5. By diagrams (Fig. 7,8) we find an angle between a tangent and a nozzle axis on a shear θ_a, and also an auxiliary angle μ_m

$$\begin{aligned}\theta_a &= f(M_a),\\ \mu_m &= f(T)\end{aligned}.$$

6. We calculate an angle between a tangent to a contour and an axis in critical section:

$$\theta_m = \mu_m - \frac{\pi}{2} + \sqrt{\frac{n+1}{n-1}}\text{arctg}\left(\sqrt{\frac{n-1}{n+1}}\text{ctg}\mu_m\right). \tag{14}$$

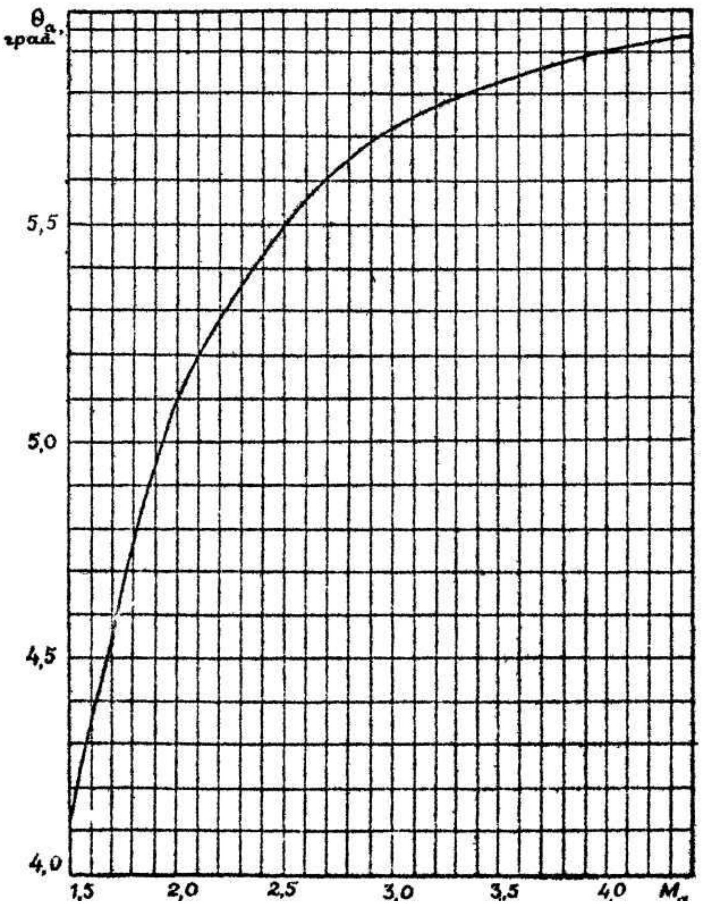

Fig. 7 Relation of output a angle from a Mach number

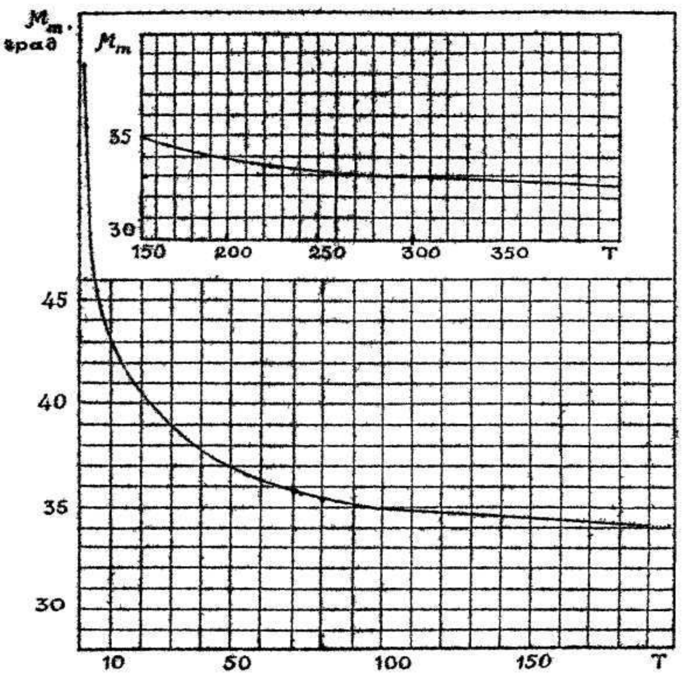

Fig. 8. Relation of an angle μ_m from parameter T

7. We calculate a contour of the nozzle supersonic part by relation

$$y = L_{соп}\left[\bar{y}_m - (1-\bar{x})tg\theta_a - (y_a - y_m - tg\theta_a)f\right]; \qquad (15)$$

$$f = \frac{\varepsilon + \tau - \varepsilon^2}{\varepsilon + \tau + \alpha^2 - 2\alpha\varepsilon}(1-\bar{x})^{\alpha} + \frac{(\alpha - \varepsilon)^2}{\varepsilon + \tau + \alpha^2 - 2\alpha\varepsilon}(1-\bar{x})^{\frac{\alpha\varepsilon - \varepsilon + \tau}{\alpha - \varepsilon}};$$

$$\varepsilon = \frac{tg\theta_m - tg\theta_a}{\bar{y}_a - \bar{y}_m - tg\theta_m}.$$

Here α and τ can be found by diagram (fig. 9).

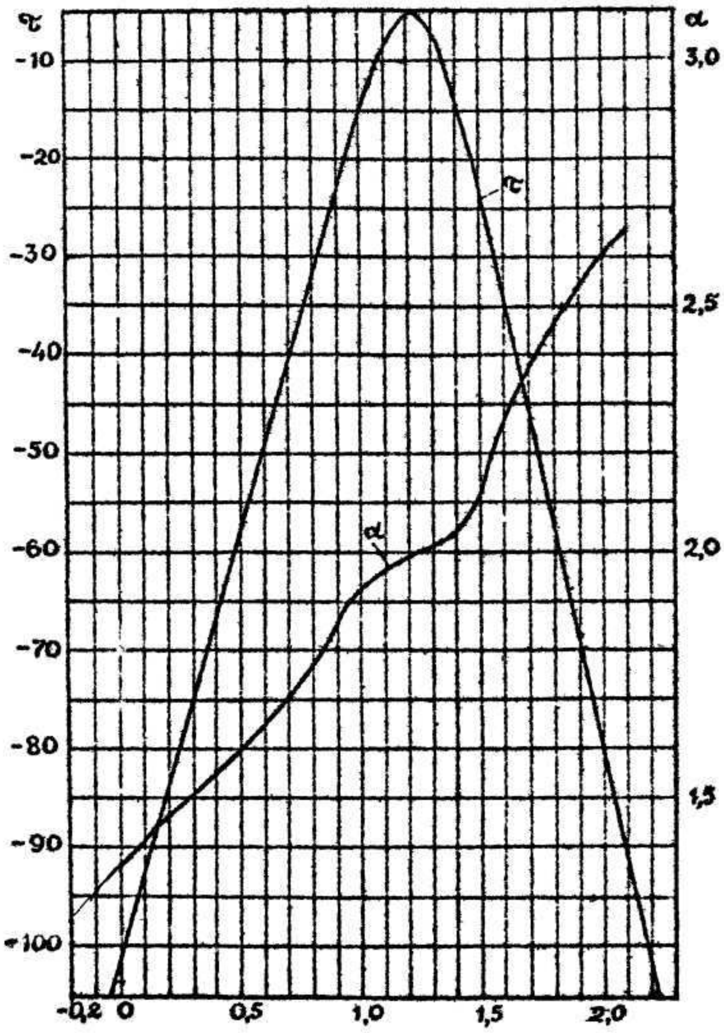

Fig. 9. Relation t and a from parameter e

It is necessary to set a number of values $\overline{x}$ in limits from 0 to 1 and to calculate values matching to them $\overline{y}$ for calculation of a supersonic nozzle contour. The nozzle contour is construction under the received data. Following conditions should be satisfied at construction:

$$\overline{y}_a = \frac{d_a}{2L_{соп}}; \quad \overline{y}_m = \frac{d_{кр}}{2L_{соп}}; \quad \overline{x} = \frac{x}{L_{соп}};$$

$$x=0,\ y=R_{кр},\quad \frac{dy}{dx} = tg\theta_m;$$

$$x=L_{соп},\ y=R_a,\quad \frac{dy}{dx} = tg\theta_a.$$

3. CONSTRUCTION OF THE GAZDYNAMIC PROFILE OF THE CHAMBER OF THE LPRE

The engine chamber gasdynamic profile consists of a gasdynamic profile of the combustion chamber and the profile of a jet nozzle joined to it.

Here it is considered as the most widespread cylindrical combustion chamber with a flat mixing head. For construction of its profile it is necessary to have such design data: a chamber volume, length of a cylindrical part, diameter of the chamber, the form and length of an entering part of the nozzle.

Calculations are made on the basis of certain mathematical formalisation with use of the statistical data approximated by matching ratios. The volume of combustion chamber $V_к$ including a volume of the chamber to critical cross-section, is determined through reduced length $L_{пр}$:

$$V_к = L_{пр} F_{кр}$$

The combustion-chamber length is characterized by conditional length

$$l_к = \frac{V_к}{F_к},$$

where F_k - a cross-sectional area of the combustion chamber having diameter $d_к=2R_к$.

The relative square of chamber $\overline{F}_к = \frac{F_к}{F_{кр}}$ can be expressed through $l_к$ and $L_к$, diameter of the chamber can be determined as $d_к = d_{кр}\sqrt{\overline{F}_к}$

The analysis of statistical data shows that chamber pressure $p_к$ makes essential impact on value $L_{пр}$, and a throat diameter $d_{кр}$ - on value $l_к$. Character of a modification can be explained that intensity of working process increases and accordingly the necessary volume of the combustion chamber decreases with chamber pressure growth. The necessary length of turbulent intermixing of combustion products decreases with a diminution $d_{кр}$ because of reduction of characteristic scale of intermixing.

Following calculating ratios are used for $L_{пр}$, $l_к$ and $\overline{F}_к$:

$$L_{пр} = \frac{15 \cdot 10^3}{\sqrt{10 p_к}};$$

$$l_к = 0{,}03\sqrt{d_{кр}};$$

$$\overline{F}_к = \frac{L_{пр}}{l_к}. \qquad (17)$$

$P_к$ undertakes in Pas, $d_{кр}$- in mm, and $l_к$ - in m in reduced above approximating relations.

The form of an entering part of the nozzle is executed on two interfaced radiuses R_1=$d_{кр}$ and R_2 (fig. 10), and radius R_2 should be taken large with $p_к$ increasing. It follows from the fact, that recording low-temperature near-wall layer and (or) layer of the curtain of cooling are saved more stable at smaller curvature of a contour of an entering part of the nozzle.

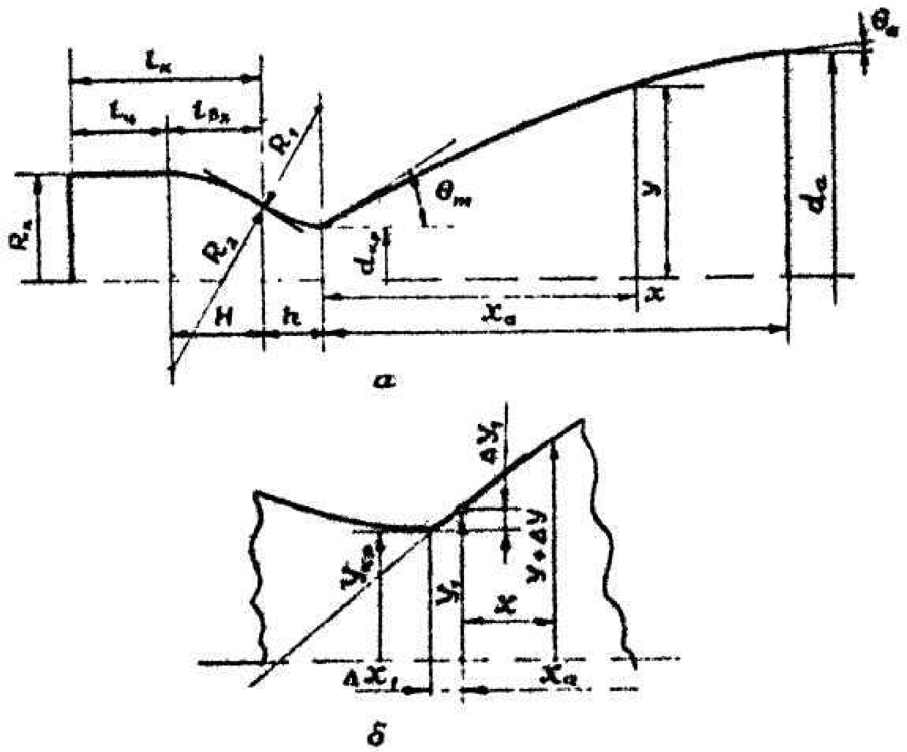

Fig. 10 Rated scheme of construction of a gasdynamic profile:

а – without a rounding off; б – with a rounding off of an angular point

It is recommended

$$\rho = \frac{R_2}{R_к} = 0,25 \cdot 10^{-6} p_к . \qquad (18)$$

For $p_к$<4 MPa ρ=1, for $p_к$>30 MPa ρ=5.

At the adopted form of an entering part of the nozzle its length

$$l_{вх} = 0,5 d_{кр} \sqrt{\left(2 + \rho\sqrt{\overline{F}_к}\right)^2 - \left[(\rho - 1)\sqrt{\overline{F}_к} + 3\right]^2} \qquad (19)$$

and co-ordinates of a point of conjugation of arcs of rounds with radiuses R_1 and R_2 will be:

$$\frac{h}{l_{вх}} = \frac{2}{2 + \rho\sqrt{\overline{F}_к}};$$

$$\frac{H}{l_{вх}} = 1 - \frac{h}{l_{вх}};$$

$$\bar{y} = \frac{y}{y_{кр}} = \frac{h}{l_{вх}}\sqrt{\bar{F}_к} + \frac{H}{l_{вх}}.$$

The length of a cylindrical part of the combustion chamber is defined by formula

$$l_ц = \frac{V_к - \Delta V_{вх}}{F_к},$$

where $\Delta V_{вх}$ - a volume of an entering part of the nozzle. For $\Delta V_{вх}$ it is possible to use approximate relation.

$$\Delta V_{вх} = F_{кр} l_{вх} \left\{ \left[\left(2\bar{F}_к + \bar{y}^2 \right) \frac{H}{3l_{вх}} \right] + \left[\left(\bar{y}^2 + \bar{y} + 4 \right) \frac{h}{6l_{вх}} \right] \right\}. \qquad (20)$$

Co-ordinates of a contour of a supersonic part of the nozzle with an angular point are computed on relations (11-15).

Designs of nozzles are known where the angular point in critical cross-section "smoothes out" by circular arc with radius r = (0,1-0,2) $d_{кр}$, which then geometrically is interfaced to a rated nozzle contour. Co-ordinates of points of mating (fig. 10) are computed under formulas

$$\Delta x_1 = r \sin \theta_m;$$

$$\Delta y_1 = r(1 - \cos \theta_m); \qquad (21)$$

$$y_1 = y_{кр} + \Delta y_1.$$

Thus, at a rounding off of an angular point the co-ordinate x should be conducted from cross-section y_1, and co-ordinate y has to be increased at the correction

$$\Delta y = \Delta y_1 \left(1 - \frac{x}{x_a} \right). \tag{22}$$