2.5. The account of losses in the engine. Definition of the valid parameters.

Accepted before an assumption have allowed to define and present in the directory the theoretical (ideal) characteristics of combustion products described above in the chamber and equilibrium expansion in nozzle.

The real processes in engines occur to an appreciable deviation from the idealized scheme. Properties of combustion products also differ from calculation it.

Movement of combustion products generally is not described by the equations one-dimensional equilibrium isentropic nozzle flow. Real nozzle flow is not one-dimensional and can be accompanied by the no equilibrium phenomena. For example, by power and chemical no equilibrium. In a biphasic stream high-speed, temperature and phase non-uniformity has essential value. As well as any real substance, products of combustion have viscosity, heat conductivity, radiating ability. They give a part of heat to walls of the chamber.

The information on qualitative structure of combustion products, $p-\nu-T$ and other properties of individual substances at high temperatures, the mechanism and speeds of chemical reactions is limited. Assumptions about ideality (in sense of the equation of a condition) individual substances, and also about chemical and power equilibrium of mixes are, strictly speaking, fair only in limiting cases ($p \to 0$, infinite time of stay). Therefore it is possible to expect known discrepancy in the calculated and real properties of combustion products.

Even at the ideal organization of processes it is necessary to expect some discrepancy of the calculated and valid thermodynamic characteristics. The real organization of processes of burning and expansion increases this discrepancy.

Incompleteness of combustion, heterogeneity of parameters of a stream on cross section of the chamber, non-adiabatic – all this can result currents in significant losses and make appreciable amendments to ideal values of characteristics. Kinds of losses and methods of definition of amendments are known well enough and widely submitted as in educational, and the special literature.

Let's consider the general reasons of the account of losses at thermal calculation of the engine.

The major characteristic of combustion products is the specific impulse in vacuum I_s^n. Therefore, first of all, it is necessary to establish connection between ideal and expected real value of its.

In view of a various kind of losses the total size of losses of a specific impulse in vacuum can be calculated under the formula:

$$\Delta I_s^n = I_{s_{ид}}^n - I_s^n = \Delta I_{s_{см}}^n + \Delta I_{s_{гор}}^n + \Delta I_{s_H}^n + \Delta I_{s_s}^n + \Delta I_{s_{тр}}^n + \Delta I_{s_p}^n, \qquad (22)$$

where $\Delta I_{s_{см}}^n$ - the losses of a specific impulse connected to heterogeneity of structure and properties of products of combustion on cross-section of the chamber;

$\Delta I_{s_{гор}}^n -$ losses of a specific impulse on incompleteness of combustion;

$\Delta I_{s_H}^n -$ the losses connected with chemical and power non-equilibrium of process;

$\Delta I_{s_s}^n -$ losses on non-uniformity of biphase flow;

$\Delta I_{s_{тр}}^n -$losses on friction and heat exchange;

$\Delta I_{s_p}^n -$the losses connected with non-parallel of the expiration (losses on dispersion).

Or

$$\Delta I_s^n = I_{s_{ид}}^n - \sum_j \Delta I_{s_j}^n. \qquad (23)$$

the index "ид" hereinafter designates ideal (theoretical) values of the considered parameter.

The factor of a j kind of losses of a specific impulse is determined by the following formula:

$$\varphi_j = \frac{I_s^n(j)}{I_{s_{ид}}^n}, \qquad (24)$$

and the total factor of losses of a specific impulse can be written down so:

$$\varphi_{I_s^n} = 1 - \sum (1 - \varphi_i \approx \varphi_1, \varphi_2, ..., \varphi_i, ..., \varphi_n.) \qquad (25)$$

Usually factors φ_j in expression (25) unite and write down this expression as

$$\varphi_{I_s^n} = \varphi_T \cdot \varphi_C, \qquad (26)$$

where φ_T - factor of losses in the chamber, including subcritical part of a nozzle;

φ_C - factor of losses in nozzle of combustion chamber.

The degree of difference of real processes in the combustion chamber from theoretical can be submitted as

$$\varphi_\beta = \frac{\beta}{\beta_{ид}}, \qquad (27)$$

here $\beta = \frac{P_{co} \cdot F_*}{G}$ - a specific impulse of pressure in the chamber of combustion or an flow rate complex.

The size φ_β is named factor of completeness of pressure in the combustion chamber and characterizes a degree of perfection of working process in the combustion chamber. It totally characterizes completeness of combustion and loss of full pressure in a subsonic part of nozzle.

With reduction of completeness of combustion φ_β decreases, and with increase in losses of full pressure grows. At absence of the irreversible phenomena in nozzle φ_β reliably enough characterizes completeness of combustion. Otherwise on size φ_β it is impossible to judge perfection of process of combustion.

For example, at definition β in conditions $P_{co} = (P_{co})_{ид}, F_* = (F_*)_{ид}$ flow rate G owing to friction in nozzle is underestimated concerning $G_{ид}$. In a biphase flow to increase in non-uniformity between speeds of gas and particles in a nozzle there is an increase of flow rate.

Thus, in the first case high values φ_β can take place at poor quality of processes in the combustion chamber, but at the big losses on friction. At the same time in the second case low values φ_β can take place at the perfect burning.

As well as the specific impulse in vacuum, an flow rate complex β is proportional to $\sqrt{R_{co} \cdot T_{co}}$, hence, imperfection of processes in the chamber of combustion affects on β proportional to $\sqrt{R_{co} \cdot T_{co}}$.

The irreversible phenomena in a subsonic part of nozzle can be taken into account with the help of factor of the flow rate μ_c. Thus:

$$\varphi_\beta = \frac{\varphi_T}{\mu_c}. \tag{28}$$

However it is correct profiling subsonic part of a nozzle (under Vitoshinsky’s formula or an arch of radius $3R_*$) allows to come to naught practically any sort the irreversible phenomena in a nozzle (shock waves, etc.). Therefore with accuracy, sufficient for calculation, in expression (28) it is possible to put $\mu_c = 1$ and then finally the factor of losses of a specific impulse in vacuum will be written down as

$$\varphi_{I_s^n} = \varphi_\beta \cdot \varphi_c . \tag{29}$$

In some cases, for example, at calculation of the engine by entropy diagrams, losses in the combustion chamber are much more convenient for taking into account not in factor φ_T, and in factor of decrease of temperature ξ_T. This factor is the ratio of the real temperature T_{co} to theoretical $T_{co\ ид}$:

$$\xi_T = \frac{T_{co}}{T_{co\ ид}}.$$

This factor can be used at application of Handbook, for example, for definition of the real temperature in the chamber after calculations with extrapolation formulas. Roughly the factor of decrease of temperature can be accepted

$$\xi_T = 0.9 \div 0.96$$

The factor φ_c estimates losses inside supersonic part of nozzle and includes losses on friction, non- parallel of expiration process, non-isentropic of expansion process of and a various sort of gas- dynamic losses.

As the losses connected to dispersion of speed of the expiration are determined with the help of theoretical factor φ_α, factor φ_c it is possible to present as product of two factors

$$\varphi_c = \varphi_\alpha \cdot \varphi_w, \qquad (30)$$

where

φ_w - the factor which is taking into account all internal losses in a nozzle, except for losses on dispersion. It can be determined as the ratio of the real speed of the expiration from a nozzle to the theoretical speed.

$$\varphi_w = \frac{W_a}{W_{a\ ид}}; \qquad (31)$$

for modern LPRE $\varphi_w = 0.96 \div 0.98$.

φ_α – the factor which is taking into account losses on dispersion of speed of the gas expiration, caused by non-parallel of a outlet edge of a nozzle to axes of the engine.

On the physical sense the factor φ_α represents the ratio of projections to an axis of the engine of momentum of a stream of gases from a nozzle with the conic exit having a angle 2α, to momentum of a parallel stream on an exit from a nozzle.

The factor φ_α can be calculated theoretically and equal

$$\varphi_\alpha = \cos^2\left(\frac{\alpha}{2}\right). \qquad (32)$$

Calculation under the formula (32) for some corners of a solution of a nozzle is submitted in the table.

α	10	15	20	25	30
φ_α	0,9924	0,9830	0,9698	0,9532	0,9330

The factors described above on the statistical data modern LPRE roughly are in limits

$$\varphi_\beta = 0,95 \div 0,99, \; \varphi_c = 0,96 \div 0,98.$$

Thus, the information on theoretical parameters of the engine in view of losses allows to execute thermal calculation again projected real LPRE.

Let's consider the general procedure of calculation.

2.6. THERMAL CALCULATION OF LPRE WITH APPLICATION OF THE DIRECTORY

The initial data which are determined by the detailed design, for calculation are:

- absolute thrust (in vacuum P^n or on a sea level P^3);
- combustion-chamber pressure p_{co};
- pressure on a shear of the nozzle p_α ;
- propellant components « an oxidizing agent + fuel »;
- an oxidizer-to-fuel ratio α.

Absolute thrust P^n or P^3 is set on the basis of outcomes of preliminary ballistic and weight calculations of all construction. By selection of propellant components are guided by those requirements, which is most full answer assigning of a designed engine.

An oxidizer-to-fuel ratio α is assigned optimum (or close to it), i.e. such at which the specific impulse will be maximum in result.

In case of application of a construction of a engine with several chambers determined, thrust of each separate chamber for which thermal calculation is executed.

Pressure on a shear of a nozzle P_α, which characterizes altitude performance of the nozzle, is selected, is defined from required value of specific impulse in vacuum, overall dimensions and weight of the nozzle. In case of a multistage design it is taken into account, the designed engine intends for what stage.

Combustion-chamber pressure P_{co} usually select, orienting by existing designs of engines. Thus it is necessary to mean, that at $P_\alpha = const$ pressure increasing P_{co} results to decreasing of a degree of dissociation and to increment of specific impulse. Besides overall dimensions of the chamber decrease. On the other hand with increase P_{co} weight of means of fuel supply is increased.

Besides for calculation of the real parameters of the engine it is necessary to determine loss coefficients. Thus use the recommendations explained above (see .2.5).

Calculation is conducted in the following order:

1. The relevant volume of a manual in which data on calculation of combustion products and equilibrium expansion of the given fuel composition "O" + "F" are adduced is selected.

2. In this volume a series of tables with stationary values and equal to the given an oxidizer-to-fuel ratio α is selected. From this series the table, in which "reference" value is selected $P_{co}{}^{(0)}$ most close to a set value of combustion-chamber pressure. For example, let it is given $P_{co} = 13000\ кН/м^2$. For the given P_{co} from a series of tables with $\alpha = const$ and $P_{co} = 100, 200, 500, 1000, 2000, 5000, 10000, 15000, 25000, 50000\ кН/м^2$ we select the table with $P_{co} = 15000\ кН/м^2$. The table selected by such way will be in what initial "reference" datas on calculation of again designed engine are.

3. In the selected table from lines of values of "reference" expansion ratios $\varepsilon^{(0)}$ (2-d a line in the table) it is fined the most close (analogously to item 2) to the given $\varepsilon = \frac{P_{CO}}{P_{\alpha}}$.

4. From table columns 2, 3 and from a column relevant to selected $\varepsilon^{(0)}$, we make out "reference" values of parameters of an engine in the chamber, critical cross-section and on a shear of the nozzle: $T^{(0)}, \mu^{(0)}, \beta^{(0)}, I_S^{n(0)}, \bar{F}^{(0)}, C_p^{(0)}, \chi^{(0)}, (\alpha_p T)^{(0)}, (\beta_T p)^{(0)}$. Also we make out necessary relevant factors of extrapolation formulas $A_1, A_2, B_1, B_2, C_1, C_2, C_3, D_1, D_2, D_3$

5. By formula, composed on a foundation of a ratio such as (18), we determine a theoretical value of an flow rate complex β'.

$$\ln \beta' = \ln \beta^{(0)} + B_1 10^{-3} \Delta \ln p_{CO} + B_2 10^{-3} \Delta i_T,$$

where $\Delta \ln p_{CO}$– a difference of logs of a design value of pressure of the combustion chamber and a reference value;

Δi_T - an aberration of an enthalpy of fuel from a calculated enthalpy which is given in the first table line. Thermodynamic calculation is made at a calculated enthalpy.

6. Taking into account combustion chamber losses, we determine the real value of a flow rate complex:

$$\beta = \beta' \cdot \varphi_\beta$$

7. We determine a theoretical value of specific impulse in vacuum:

$$\ln I_S^{n\prime} = I_S^{n(0)} + C_1 10^{-3} \Delta \ln p_{CO} + C_2 10^{-3} \Delta i_T + C_3 10^{-3} \Delta \ln \varepsilon$$

8. We discover the real value of I_S^n:

$$I_S^n = I_S^{n\prime} \cdot \varphi_\beta \cdot \varphi_c$$

9. We determine theoretical temperature in the combustion chamber:

$$\ln T'_{CO} = \ln T_{CO}^{(0)} + A_1 10^{-3} \Delta \ln p_{CO} + A_2 10^{-3} \Delta i_T$$

10. We discover the real temperature in the combustion chamber:

$$T_{CO} = T'_{CO} \cdot \varepsilon_T$$

11. We discover the specific area of critical cross-section:

$$f_* = \frac{\beta}{p_{CO}}$$

12. We determine a theoretical relative sectional area:

$$\ln \bar{F}' = \ln \bar{F}^{(0)} + D_1 10^{-3} \Delta \ln p_{CO} + D_2 10^{-3} \Delta i_T + D_3 10^{-3} \Delta \ln \varepsilon$$

13. We determine a mean theoretical index of isentropic process of expansion of combustion products in the nozzle from p_{CO} pressure up to p_α. For this purpose we use the formula:

$$\bar{F}' = \frac{\left(\frac{2}{n'+1}\right)^{\frac{n'+1}{2(n'-1)}} \sqrt{\frac{n'-1}{2}}}{\left(\frac{p_\alpha}{p_{CO}}\right)^{\frac{1}{n'}} \sqrt{1 - \left(\frac{p_\alpha}{p_{CO}}\right)^{\frac{n'-1}{n'}}}}$$

which can be presented as the graph (fig. 2).

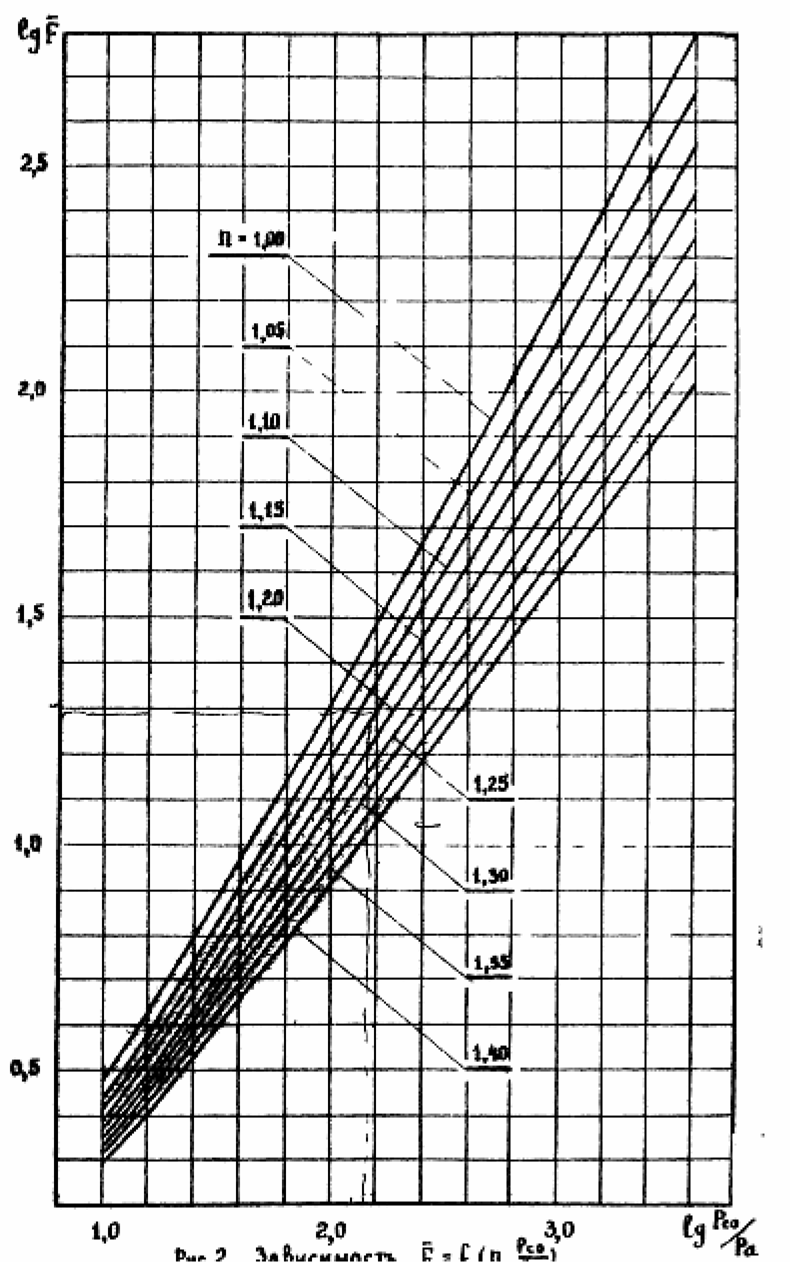


Fig. 2. relation $\overline{F} = f\left(n, \dfrac{p_a}{p_{co}}\right)$

For set values of p_{CO} and p_α (and therefore $\frac{p_{CO}}{p_\alpha}$), and a calculated value of $\bar{F}'$ we find value of n'.

14. We determine a mean molecular weight of combustion products in the chamber (see 5, tab. 1 and the formula 17):

$$\ln \mu_{CO} = \ln \mu_{CO}^{(0)} + \left[\frac{R_0}{C_p \mu}\left(\alpha_p T - \frac{\mu}{\mu_{CO}}\right) + \frac{\alpha_p T R_0}{C_p \mu_{cp}} + \frac{\beta_T P}{\chi} - 1\right] \Delta \ln P_{CO}$$

15. We define a gas constant of yields of combustion in the chamber:

$R_{CO} = \frac{R_0}{\mu_{CO}}$, где $R_0 = 8314$ Дж/кг · °К

16. We define theoretical exhaust velocity of combustion products on a nozzle shear

$$W'_\alpha - \sqrt{2\frac{n'}{n'-1}R_{CO}T_{CO}[1-(\frac{P_\alpha}{P_{CO}})^{\frac{n'-1}{n'}}]}$$

17. We define a real velocity of yields of combustion products on a nozzle shear

$W_\alpha = W'_\alpha \cdot \varphi_W$

18. We define the real index of process of expansion of yields of combustion in the nozzle by formula $W_\alpha = \sqrt{2\frac{n'}{n'-1}R_{CO}T_{CO}[1-(\frac{P_\alpha}{P_{CO}})^{\frac{n'-1}{n'}}]}$. We are making it setting a number of values n at known and fixed values $R_{CO}, T_{CO}, P_\alpha, P_{CO}$, calculating W_α, and finding n graphically (fig. 3 see)

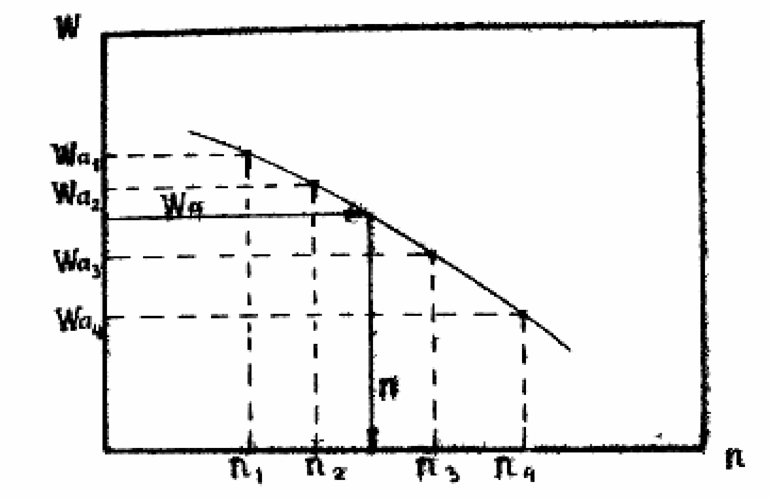


Fig. 3. To definition of n

19. We discover real relative area of section using a drawing (fig. 2):

$\bar{F} = f(n, \frac{P_{CO}}{P_\alpha})$

20. We discover specific area of a shear of the nozzle:

$f_\alpha = F \cdot f_*$

21. We define real value of specific impulse for earth conditions $I_S^3 = I_S^n - f_a P_0$ where P_0 – atmospheric pressure

22. We discover the real summarized flow rate of propellant components on one of formulas

$$G = \frac{P^3}{I_S^3} \text{ или } G = \frac{P^n}{I_S^S}$$

It depends on type of a designed engine (earth or high-altitude).

23. We define area of critical section of the combustion chamber and a throat diameter

$$F_* = f_* G; \quad d_* = \sqrt{\frac{4F_*}{\pi}}$$

24. We define area of a shear of the nozzle and diameter of a shear of the nozzle:

$$F_a = f_a G; \quad d_a = \sqrt{\frac{4F_a}{\pi}}$$

25. We discover flow rate of propellant components: !!!!

$$G_0 = \frac{H_1 G}{1 + K_1}; \quad G_r = \frac{G}{1 + K_1}$$

Where K_1 – a weight number of components ratio of the fuel, matching to a preset value of α which value is given in the first table line 1

26. We discover real flow parameters in critical section

$$a)\ P_* = P_{CO}\left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}$$

$$b)\ T_* = T_{CO}\frac{2}{n+1}$$

$$c)\ W_* - \sqrt{\frac{2n}{n+1}R_{CO}T_{CO}}$$

3. THERMAL CALCULATION OF THE ENGINE WITH USE DIAGRAMMES "ENTHALPY-ENTROPY"

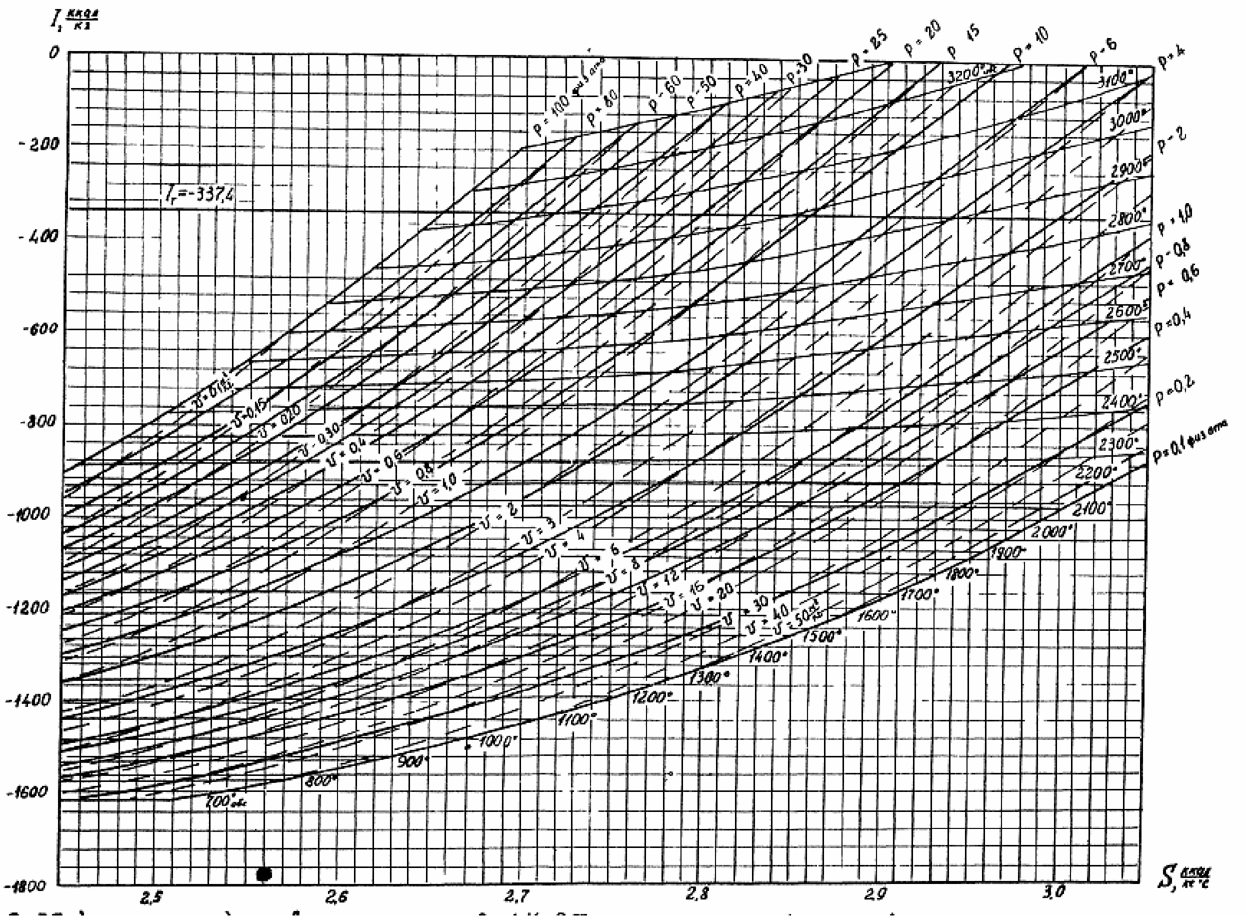
3.1. Entropy diagrammes of yields of combustion.

The greatest difficulties originate at definition of a structure and temperatures of combustion products in the chamber and on a nozzle shear. It does not depends on a method of thermodynamic calculation of combustion and the expiration of equilibrium dissociated of combustion products at heats of combustion which is advanced in the LPRE owing to application of liquid oxidising agents. This calculation demands a lot of time and transactionses. Meanwhile, the structure and temperature of combustion products is necessary for knowing only to compute molecular weight, an enthalpy and entropy without which it is impossible to determine key parameters of an engine and nozzle sizes. In other words, data of thermodynamic calculation are initial and necessary for calculation of the chamber of the LPRE. There is a problem on a capability of conducting of thermal calculation of the LPRE under in advance built diagrammes «Full entropy - an enthalpy» (IS - diagrammes). They is short are called as entropy diagrammes.

The entropy diagramme is calculated and under construction for quite certain fuel, i.e. for particular components and the given oxidizer-to-fuel ratio (or weight components ratio). Therefore this or that diagrammes can be applied only to calculations of engine which are designed and work with this propellant.

The entropy diagramme is a grid organized by curves at least of three types: isobars, isothermals and isochors. Sometimes additional lines are put on entropy diagrammes except the indicated base lines. It allows discovering exhaust velocity and geometrical sizes of the nozzle directly. Any point of this grid characterises a thermodynamic state of equilibrumly dissociated of combustion products of the given propellant.

Here we give as an example the entropy diagram for some a liquid nitric acid and nonsymmetrical dimethylhydrazine.



The IS diagram of fuel combustion products of nitric acid + nonsymmetrical dimethylhydrazine at α = 0,8

At calculation of these diagrammes the updated data on thermal constants of combustion products were received. All diagrammes are constructed for enough pressure broad band ($0{,}1 \cdot 10^5 \frac{Н}{м^2} - 100 \cdot \frac{10^5 Н}{м^2}$) and necessary limits of temperatures in practice for chosen fuels. It is necessary to notice, that on entropy diagrams pressure is indicated usually in physical atmospheres as in the majority of tables standard entropies of gases are given for this unit of pressure measurement. The oxidizer-to-fuel ratio for each pair of components is chosen to optimum or close to it. To construct dense enough grid of isobars, isotherms and isochors, calculations were made for each diagramme in 200-300 computational points of equilibrium conditions of the dissociated products of combustion.

For definition of the engine’s real characteristics (taking into account losses) are used described above (item 2.5 see.) corresponding factors.

3.2. Thermal calculation of the engine by IS – diagram

Calculation is conducted in a following order.

1. On interception of a full enthalpy line of initial fuel $I_T = I'_{CO}$ and isobars, corresponding to the set combustion-chamber pressure P_{CO}, there is a point C', that determinate theoretical parameters of combustion products in the chamber – temperature T'_{CO}, specific volume V'_{CO} and entropy S'_{CO} (Fig. 4).

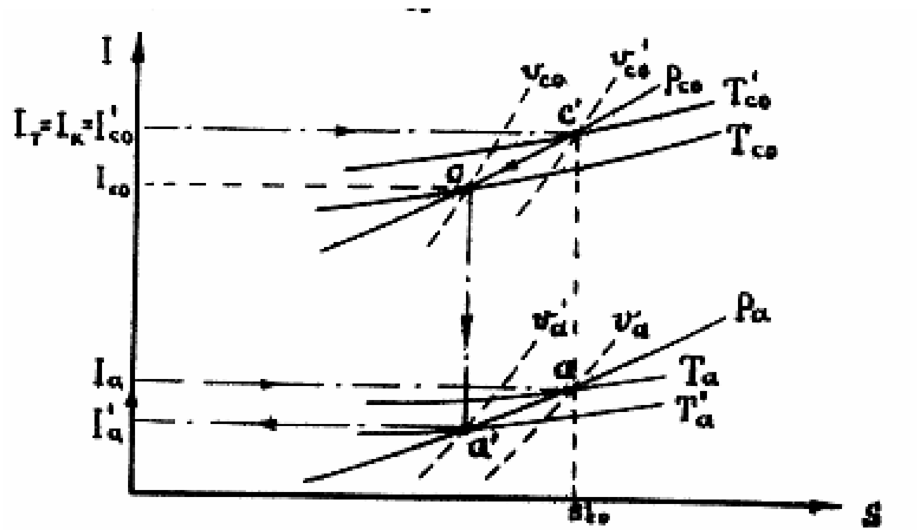


Fig. 4. The scheme of thermodynamic calculation under the diagramme

2. The real temperature of products in the chamber is calculated $T_{CO} = T'_{CO} \cdot \varepsilon_T$.

3. We find a point of interception *C* of isotherm $T_{CO}T_{CO}$ with isobar $P_{CO}P_{CO}$. This point determines the real value of enthalpy $I_{CO}I_{CO}$ and specific volume $V_{CO}V_{CO}$ of combustion products in the chamber.

4. We realize that process of the gases expiration is adopted isentropic, that means $S_{CO} = S_\alpha S_{CO} = S_\alpha$, there are theoretical values of parameters on a nozzle

shear. For this purpose from point *C* we are lowered vertically down to interception with the isobar corresponding to set pressure on shear $P_\alpha P_\alpha$. The point of interception $\alpha'\alpha'$ gives value of parametres $I'_\alpha I'_\alpha$ of an enthalpy on a shear, $T'_\alpha - T'_\alpha -$ temperatures and $V'_\alpha V'_\alpha$ - a specific volume of flowing gases.

5. Theoretical exhaust velocity of gases from the nozzle is calculated

$$W'_\alpha = \sqrt{2(I_{CO} \quad I'_\alpha)} \text{ м/с}$$

Where the enthalpy is substituted in J/kg. (if IS – diagrammes are resulted in MCS system and it is necessary to translate the values removed from schedules preliminary in this system, meaning that 1 kcal/kg = 4187 J/kg).

6. We find the real exhaust velocity of gases from the nozzle

$$W_\alpha = W'_\alpha \cdot \varphi_W, \text{м/с}$$

7. We determine the real enthalpy on a nozzle shear

$$I_\alpha = I_{CO} - \frac{W_\alpha^2}{2}, \text{Дж/кг}$$

8. Having conducted from point $I_\alpha I_\alpha$ a line in parallel to axes OS before interception with isobar $P_\alpha P_\alpha$, we receive a point α which determines the real parameters on T_α nozzle shear $T_\alpha V_\alpha V_\alpha$.

9. We calculate average value of isentropic parameter expansions

$$n = \frac{\lg \frac{P_{CO}}{P_\alpha}}{\lg \frac{V_\alpha}{V_{CO}}}$$

10. We determine parametres of a gas flow in critical section:

a) $P_* = P_{CO}(\frac{2}{n+1})^{\frac{n}{n-1}}$ – Pressure

b) $V_* = V_{CO}(\frac{n+1}{2})^{\frac{1}{n-1}}$ - Specific volume

c) $T_* = T_{CO}(\frac{2}{n+1})$ - Temperature

d) $W_* = \sqrt{nP_*V_*}$ - Speed

11. We find the specific area of a stream on a nozzle shear:

$$f_\alpha = \frac{V_\alpha}{W_\alpha}$$

12. We calculate chamber specific impulse on a sea level:

$$I_S^3 = \varphi_\alpha[W_\alpha - f_\alpha(P_\alpha - P_0)], \text{м/с}$$

Where $P_п$ – Ambient pressure on a sea level.

13.We determine specific impulse in vacuum:

$$I_S^n = I_S^3 - \varphi_\alpha \cdot f_\alpha \cdot P_0, \text{м/с}$$

14.We calculate second propellant flow rate and its components:

$$G = \frac{P^3}{I_S^3} \left(\text{или } G = \frac{P^n}{I_S^n} \right);$$

$$G_0 = \frac{K_1 G}{1 + K_1}; \quad G_г = \frac{G}{1 + K_1}$$

Here K_1 – Components ratio factor in the combustion chamber, that is equal to $K_1 = \alpha \cdot H_0$

Where H_0 – stoichiometrical factor of components ratio for the given fuel.

15.We determine an absolute thrust in vacuum or on the earth (depending on what is set in a design building):

$$P^n = I_S^n G, \quad (P^3 = I_S^3 G)$$

16.We calculate the area of critical section and a nozzle shear:

$$F_* = G f_*; \quad F_\alpha = \varphi_\alpha \cdot G \cdot f_\alpha$$

17.We calculate diameters of the chamber in critical section and for a nozzle shear:

$$d_* = \sqrt{\frac{4P_*}{\pi}}; \quad d_a = \sqrt{\frac{4F_\alpha}{\pi}}$$