§1. MAIN POSITIONS

Thermal calculation of a designed engine is made with the purpose of definition of the main sizes of the nozzle, specific impulse and the flow rate of propellant components. It includes:

- thermodynamic calculation of a structure and temperatures of the dissociated of combustion products in the chamber and on a shear of the nozzle;
- gas-dynamic calculation.

Thermodynamic calculation of combustion and the expiration in liquid rocket engine (LPRE) is made at following basic conjectures:

1) Mixing of propellant components completely. Up and down chambers their weight ratio (or an oxidizer-to-fuel ratio) is equal;

2) the response of combustion is completely completed to the end of the combustion chamber and flows past at constant chamber pressure $p_к$;

3) on an input in the nozzle (at the end of the chamber) the dissociated of combustion products stay in a condition of full equilibrium (power and chemical), no less than in any cross-section of the nozzle, in particular on its shear;

4) nozzle flow is isentropic, one-dimensional and steadied.

These conjectures correspond to conditions of thermodynamic cycle of LPRE. Therefore parameters of the engine which receive as a result of thermodynamic calculation of combustion and the expiration, it is necessary to consider as theoretical.

It means, that thermodynamic calculation does not take into account loss because of a non-equilibrium of process of the expiration and the real losses stipulated physical no complete combustion of fuel, friction and a heat exchange with a circumambient.

Let's consider the computational scheme of the combustion chamber of the engine with the image of characteristic cross-sections (fig. 1).

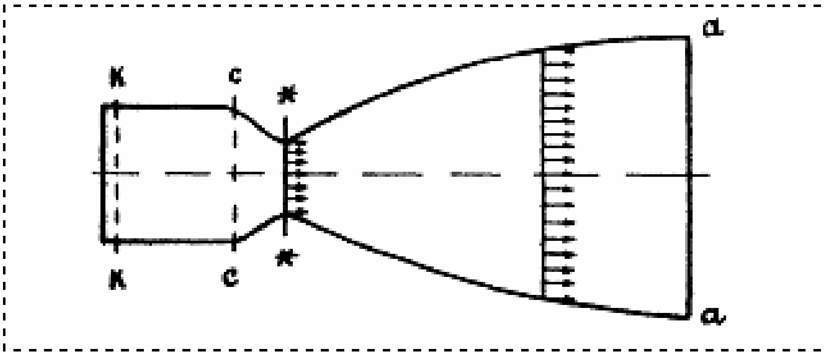

Fig. I. The scheme of the engine chamber

Main equation for definition of temperature and a structure of combustion products in the engine is the equation of conservation of energy. It is recorded for a mass unit of fuel as follows:

$I_{co} - I_T = 0,$ (1)

where I_{co}- is enthalpy of stagnated flow on an exit from the combustion chamber (on an input in the nozzle),

I_T – an enthalpy of fuel.

Hereinafter the index "0" means parameters of the stagnated flow.

At implementation of process of combustion in the isobaric combustion chamber (most widely used now) the velocity of a propulsive mass in its limits is negligiblely small and is received equal to null. It stipulates possibility of using of following ratio:

$p_к = p_{кo} = p_c = p_{co}$;

$T_c = T_{co}$

The equation of energy (1) receives thus the individual form:

$I_c = I_T.$ (2)

In such kind it also is used at calculation of temperature of combustion products in usual isobaric chambers ($p_{кo} = p_{co} = const$), at which $F_к >> F_*$.

For velocity chambers at which the throat diameter is only a little less of diameter of the combustion chamber (in extreme case $F_к = F_*$), it is necessary to take into account a kinetic energy of gases, and also pressure drop on a combustion-chamber length. For this purpose it is necessary to use in addition momentum equation. However such chambers now are not applied almost.

Main difficulty at realization of thermodynamic calculations is reduced to finding of an equilibrium structure of combustion products at the given temperature.

For definition of a structure of of combustion products at the given temperature the set of equations including is made:

- balance equation of elements,
- equations of chemical equilibrium,
- equations of partial pressures.

Main equation for definition of temperature and a structure of combustion products on a shear of the nozzle is the equality of entropies in the combustion chamber and on a shear:

$$S_к = S_a, \qquad (3)$$

which expresses a condition of isoentropic process of expansion in the nozzle. For calculation of a structure of combustion products on a shear of the nozzle at the given temperature the same set of equations, as for the combustion chamber is used.

Definition of an equilibrium structure is a part of many problems of high-temperature power engineering and is characterized by a large variety of methods of calculation. The most full informations about methods of calculation of a structure can be found in the theory and designing of rocket engines works.

Now on the basis of general methods of the solution of a set of equations the corresponding computer programs are created, permitting to make such calculation for any given temperature with an adequate accuracy.

Thus, from thermodynamic calculation of combustion of fuel and the expiration combustion products there are known main necessary parameters of the engine:

а) In the combustion chamber

$p_к = p_{co}$,

$I_т = I_к$,

$T_к = T_{co}$,

$\upsilon_к = \upsilon_{co}$;

б) On a shear of the nozzle

p_a, I_a, T_a, υ_a.

Gas- dynamic calculation of the engine is made under the scheme of calculation of the combustion chamber which works on a theoretical cycle of process of the expiration and combustion.

Theoretical process in chamber LPRE means a full born-out of fuel to the end of the combustion chamber and presence of an equilibrium structure of combustion products during isentropic expansion.Thus losses of heat for dissociation in the combustion chamber and returning of a part of heat because of a recombination in the nozzle are taken into account only.

Let's consider fulfilment of thermal calculation of the engine with application:

1) the directory « Thermodynamic and thermal properties of combustions products»;

2) diagram « the Full enthalpy – an entropy ».

§2. THERMAL CALCULATION OF THE ENGINE WITH DIRECTORY USE «THERMODYNAMIC AND THERMAL PROPERTIES OF COMBUSTION PRODUCTS»

2.1. The description of the Directory tables

The directory represents a fundamental reference media about a structure and properties of combustion products of modern high-energy chemical fuels and their equilibrium expansion in nozzles.

Thermodynamic and gas dynamics calculations are executed on the basis of initial data about thermal constants and thermodynamic properties of the individual substances which are a part of fuel and products of combustion. The general methods of solution of equations systems for structure definition of combustion products at the set temperature and known gas dynamics ratio are used.

The basic form of calculation results representation in the Directory is tabular. The example of the directory tables is presented in table 1. In tables there are placed types of thermodynamic properties of combustion products in the set range of determining conditions change. Data which can be received simple by additional calculations, are not resulted in tables.

I	$\alpha_{ок}$ = I,000 K_1 = 3,062 $\rho_т$ = I,I4I $i_т$ = 7,853 S = 2,5I9									
	ОСНОВНЫЕ ВЕЛИЧИНЫ									
2	ε	I,000	I,73I	I00,0	300,0	500,0	I000,	3000,	5000,	I0000
3	p	I00,0	57,78	I,000	,3333	,2000	,I000	,0333	,0200	,0I00
4	T	3452,	3272,	2I55,	I854,	I7II,	I520,	I242,	II25,	980,7
5	μ	24,90	25,I9	26,87	27,06	27,I0	27,I2	27,I3	27,I3	27,I3
6	a,M	II45,	I,000	3,266	3,767	4,0II	4,368	4,997	5,3I5	5,773
7	n	-	I,I35	I,I35	I,I4I	I,I45	I,I5I	I,I6I	I,I65	I,I7I
8	w	-	II06,	2864,	3092,	3I8I,	3288,	3426,	3479,	3543,
9	$\beta, I_s^{п}$	-	I722	3I58	334I	34I2	3497	3607	3649	3700
I0	$\bar{F}$	-	I,000	I3.78	32,72	48,84	83,92	I97,3	293,4	502,3
II	c_{pf}	,4573	,4549	,43I8	,4202	,4I34	,4029	,3843	,3753	,3630
I2	c_p	I,202	I,I78	,6533	,50I2	,4548	,4I59	,3855	,3756	,3630
I3	η	I003,	966,I	7I5,2	64I,I	604,7	554,0	474,9	439,5	393,I
I4	λ_f	705,0	67I,2	455,2	394,5	365,0	325,0	264,7	238,9	206,4
I5	λ	233I,	2I66,	756,9	487,4	4II,2	336,8	264,8	239,0	206,5
I6	$\varkappa$	I,I66	I,I59	I,I57	I,I84	I,I99	I,2I6	I,235	I,242	I,253
I7	a_pT	I,482	I,448	I,096	I,030	I,0I4	I,004	I,000	I,000	I,000
I8	$\beta_т$P	I,026	I,022	I,003	I,00I	I,000	I,000	I,000	I;000	I,000
I9	z	-	-	-	-	-	-	-	-	-
	I	2	3	4	5	6	7	8	9	I0

Продолжение

	КОЭФФИЦИЕНТЫ ЭКСТРАПОЛЯЦИОННЫХ ФОРМУЛ									
20	A1,C1	32,02	-	5,392	4,055	3,508	2,898	2,I84	I,923	I,6I8
2I	A2,C2	,24II	-	,I993	,2I33	,2I98	,2277	,2375	,24I4	,246I
22	B1,C3	-	9,405	59,08	44,I8	38,59	32,2I	24,42	2I,5I	I8,II
23	B2,D1	-	,I779	-I6,92	-23,9I	-26,42	-28,38	-29,24	-29,38	-29,59
24	D2	-	-	,II62	,2I50	,2597	,3046	,3455	,3604	,38I5
25	D3	-	-	786,0	785,6	782,6	779,4	777,4	776,4	774,2
26	A4,C4	-964,0	-	-87,05	-I00,0	-I08,7	-I22,5	-I40,9	-I47,8	-I56,2
27	B4,D4	-	-43,86	-I,708	-II,I5	-26,95	-76,03	-236,6	-368,2	-662,I
28	L4	-	-	-	-	-	-	-	-	-
29	A5,C5	-I742,	-	-39,27	-57,95	-74,24	-I0I,5	-I33,6	-I45,3	-I59,I
30	B5,D5	-	-I2,02	-4,I66	-23,66	-60,29	-I7I,3	-49I,5	-748,6	-I307,
3I	L5	-	-	-	-	-	-	-	-	-
	I	2	3	4	5	6	7	8	9	I0

Продолжение

РАВНОВЕСНЫЙ СОСТАВ

32	O	,0083	,0064	,0002	-	-	-	-	-	-
33	H	,0094	,0075	,0003	-	-	-	-	-	-
34	O_2	,0354	,0329	,0065	,0019	,0009	,0002	-	-	-
35	H_2	,0311	,0272	,0046	,0015	,0008	,0002	-	-	-
36	OH	,0474	,0400	,0037	,0008	,0003	-	-	-	-
37	HO_2	,0002	,0001	-	-	-	-	-	-	-
38	H_2O	,3483	,3617	,4337	,4413	,4430	,4441	,4444	,4444	,4444
39	N_2	,2961	,3015	,3296	,3323	,3329	,3332	,3333	,3333	,3333
40	NO	,0197	,0161	,0013	,0003	,0001	-	-	-	-
41	CO	,0869	,0776	,0115	,0031	,0013	,0003	-	-	-
42	CO_2	,1170	,1288	,2086	,2186	,2207	,2219	,2222	,2222	,2222
	1	2	3	4	5	6	7	8	9	10

Each table contains data on combustion products of the given fuel composition at the fixed values of an oxidizer-to-fuel ratio α and combustion-chamber pressures (on an input in the nozzle) $p_K = p_{CO}$ for group of "reference" points – the most typical combinations of entry conditions. At pressure p_{CO} parameters of combustion process are characterised; parameters of equilibrium expansion process are presented for a series of expansion ratio values of a propulsive mass

$$\varepsilon = p_{CO} / p_i,$$

(Where pi - current expansion pressure in a supersonic part of the nozzle). Among it necessarily there is a critical expansion ratio ε_* and group of the supercritical values ε, chosen from a number 5, 10, 20, 30, 50, 100, 200, 300, 500, 1000, 2000, 3000, 5000.

Value of pressure p_{CO} for the majority of the fuel compositions presented in the directory, should be chosen from numbers 100, 200, 500, 1000, 2000, 5000, 10000, 15000, 25000, 50000 кN/m^2.

2.2. Definition of basic parameters in "reference points"

The information contained in the table, it is possible to divide into some kinds, and each of them takes group of lines or a table column.

Data on fuel is the first line

$\alpha_{ОК}$ – oxidizer-to-fuel ratio ;

$к_1$ - weight factor of fuel components ratio, kg "O"/kg «F» ;

$\rho_T * 10^3$ – average density of fuel, kg/m^3 ;

i_T - fuel enthalpy, kJ/kg ;

s – specific weight entropy, kJ/kg*K.

The basic values of lines $2 \div 5$

ε - expansion ratio by pressure ;

p – pressure , кN/ m^2 ;

μ - average molecular weight of a mix, kg/mol ;

General characteristics of processes of lines $6 \div 10$

a, M – speed of a sound in equilibrium reacting mix (a), m/s, for conditions on an input in the nozzle;

Mach number (M) for values $\varepsilon > \varepsilon *$

n – average index of isentropic expansions in an interval from p_{co} to $p = p_{co} / \varepsilon$;

W – flow velocity, m/s ;

β , I_s^n - chamber pressure specific impulse (account complex) β,m/s , for value $\varepsilon = \varepsilon *$;

specific impulse in vacuum I_s^n, m\s, for values $\varepsilon > \varepsilon *$

$\overline{F}$ - Geometrical expansion ratio (the relative area) .

Thermodynamic properties in lines $11 \div 19$

C_{pf} – Specific heat of a nonreacting mix at constant pressure, kJ/kg*K;

C_p - Specific heat of equilibrium reacting mix at constant pressure , kJ/kg*K;

$\eta * 10^7$ - Factor of a gas mix dynamic viscosity , N∗s/ m^2 ;

λ_f - Thermal conductivity of a nonreacting gas mix, W/m*K;

$\chi = C_p / C_V$ – Ratio of equilibrium specific heats at constant pressure and a constant volume ;

$\alpha_p \times T$ – Product of an isobar expansion ratio on temperature.

$\beta_T \times p$ – Product of compression isothermal factor on pressure ;

z – Total weight share of substances in the condensed condition.

Factors extrapolation formulas in lines $20 \div 31$

Factors represent partial derivatives of the basic values T, β, I_s^n, $\overline{F}$, z , by the basic determining parametres p_{co}, i, ε at constants the others necessary for the information obtaining out of "reference" points.

Equilibrium structure in lines $32 \div 42$

Here are presented mole shares x_i of the gaseous individual substances designated by symbols of chemical compounds O, H, … , CO in such a manner that

$\sum X_i = 1$.

The first column of the table contains designations of resulted values (ε, p , T , … Etc.)

The second column corresponds to value of values in the combustion chamber (CC), on an input in the nozzle (stagnation pressure p_{co}).

The third column – critical section (pressure $p_ж = p_{co} * \varepsilon *$).

The fourth column and the subsequent – the values of parametres corresponding to current expansion ratios.

Let's pay attention, that in the first column of the table meet on two determined values, for example :

6. a, M

……………………..

9. β, I_s^n

Etc.

Therefore in order to avoid possible errors it is necessary to remember, that each of values corresponds to certain value of expansion ratio ε. For example:

β - The account complex corresponding to critical section ($\varepsilon = \varepsilon_*$);

It is necessary to search for its value in the third column;

I_s^n - The specific impulse corresponding to the flowing $\varepsilon = \varepsilon_i$;

it is necessary to search for its value in a column corresponding ε_i.

Thus, it is direct from tables for set pair of propellant components in "reference" points (i.e. for a number of values p_{CO} and ε)it is possible to receive thermodynamic and gas dynamics engine parameters in the combustion chamber, on a shear of the nozzle and data about properties of combustion products.

2.3. Obtaining of the additional information

The data received in "reference" points, can be expanded and added by simple conversions on known theoretical ratio. So, if necessary it is possible to determine a gas constant for mix:

$R = R_O / \mu$, (4)

where R_O = 8,314 KDg/ kg$*$ degree.

By means of the equation of state the specific volume of a mix can be determined:

$\upsilon = Ro * T / \mu * p$ (5)

or its density

$\rho = 1/\upsilon$ (6)

and so on.

By means of the fundamental quantities resulted in tables, it is possible to receive also all necessary remaining parameters of the engine.

The specific square of critical section:

$f_* = \beta / p_{co}$ (here $f_* = F_* / G$, $m^2 * s/kg$) (7).

The specific square of section of a shear of the nozzle

$$f_a = \bar{F} \cdot f_*, m^2 \cdot s/kg \quad (8)$$

Specific impulse at arbitrary altitude

$$I_s = I_s^n - f_a \cdot p_н, \ m/s$$

Specific impulse on land (standard atmospheric pressure is p_0)

$$I_s^з = I_s^n - f_a \cdot p_0 \quad (9)$$

Summarised propellant consumption

$$G = \frac{P^з}{I_s^з}, \quad kg/s \quad \text{or} \ G = \frac{P^n}{P_s^n}, kg/s \quad (10)$$

The squares of sections

a) The critical sections $F_* = f_* \cdot G, m^2$ (11)

б) A nozzle shear sections $F_a = f_a \cdot G, m^2$ (12)

Oxidizer consumption $G_0 = \frac{K_1 \cdot G}{1 + K_1}, kg/s$ (13)

Fuel consumption $G_Г = \frac{G}{1 + K_1}, kg/s$ (14)

Where $К_1$ - the weight number of components ratio determined under the table.

Application of methods of extrapolation and interpolation is used in the Manual for obtaining of parameters of the engine on initial data (p_{co}, ε) being inside or out of a field of "reference" points.

The method of expansion of function in Taylor series is applied to extrapolation in Directory:

$$f(\chi_1, \chi_2, ..., \chi_i, ..., \chi_n) = f(\chi_1^0, \chi_2^0, ..., \chi_i^0, ..., \chi_n^0) + \sum_{i=1}^{n} (\frac{\partial f}{\partial \chi_i})^0 \cdot (\chi_j - \chi_i^0) + \frac{1}{2} \sum_{ij} (\frac{\partial^2 f}{\partial \chi_i \cdot \partial \chi_j})^0 \cdot (\chi_i - \chi_j^0) \cdot (\chi_j - \chi_j^0)...,$$

$$i, j = 1,2,3,..., n \quad (15)$$

At unknown second derivations of function the equation (15) is used only with the first two members. Special form of function and arguments is selected for obtaining of necessary extrapolation accuracy. In this case numerical values of derivatives in the interval of extrapolations are close to constants.

For interpolation the polynomial of such aspect is used

$$У = К_0 + К_1 \cdot X + К_2 \cdot X^2 + К_3 \cdot X^3. \qquad (16)$$

Polynomial factors were found from the joint solution of the equations including values of function and its first derivatives in two points according to thermodynamic calculation.

2.4. Definition of parameters of the engine out of or in a field of "reference" points.

As already it was indicated above, the basic interpolation in the Manual is included in a number of "reference" points. In practice usually the set parameters of the engine differ from these "reference" values. In other words, preset values of combustion-chamber pressure $p_k = p_{co}$ and expansion ratios ε do not coincide with one reference value from rows $p_{co} = 100{,}200{,}...{,}50000 kN/m^2$ $\varepsilon = 5{,}10{,}...{,}5000.$; In these cases engine parametres are necessary for computing on the basis of "reference" values, using extrapolation and interpolation methods.

Let's observe application of a method of extrapolation for definition of parameters in characteristic sections of the combustion chamber.

In the Manual the general formulas for some extrapolated property of yields of combustion φ are received (value of function and derivatives in "reference" points are marked by a superscript "null").

Entry in the nozzle. Extrapolation on pressure p_{co} and enthalpies i_{co} is possible. It is possible to size up agency of a modification of reference temperature of fuel and thermal combustion chamber losses (cooling, not complete combustion) by an enthalpy modification. This case matches to condition $\varepsilon = \frac{p_{co}}{p} \to 1$:

$$\ell n\varphi = \ell n\varphi^{(0)} + (\frac{\partial \ell n\varphi}{\partial i_{co}})^{(0)}_{p_{co},\varepsilon} \Delta i_{co} + (\frac{\partial \ell n\varphi}{\partial \ell n p_{co}})^{(0)}_{i_{co},\varepsilon} \Delta \ell n p_{co}. \qquad (17)$$

<u>Critical section of the nozzle (M=1).</u> Extrapolation on the same parametres at an assumption $\varepsilon_* = \text{const}$:

$$\ell n\varphi = \ell n\varphi^{(0)} + (\frac{\partial \ell n\varphi}{\partial i_{co}})^{(0)}_{p_{co},\varepsilon_*} \Delta i_{co} + (\frac{\partial \ell n\varphi}{\partial \ell n p_{co}})^{(0)}_{i_{co},\varepsilon_*} \Delta \ell n p_{co}. \qquad (18)$$

<u>Output nozzle section</u>. Extrapolation is possible at various combinations of explanatory variables:

а) if the explanatory variables are: i_{co}, p_{co}, p_a :

$$\ell n\varphi = \ell n\varphi^{(0)} + (\frac{\partial \ell n\varphi}{\partial i_{co}})^{(o)}_{p_{co},p_a} \Delta i_{co} + (\frac{\partial \ell n\varphi}{\partial \ell n p_{co}})^{(0)}_{i_{co},p_a} \Delta \ell n p_{co} + (\frac{\partial \ell n\varphi}{\partial \ell n p_a})^{(0)}_{i_{co},p_{co}} \Delta \ell n p_a; \qquad (19)$$

б) if the explanatory variables are: $i_{co}, p_{co}, \overline{F}_a$:

$$\ell n\varphi = \ell n\varphi^{(0)} + (\frac{\partial \ell n\varphi}{\partial i_{co}})^{(0)}_{p_{co},\overline{F}_a} \Delta i_{co} + (\frac{\partial \ell n\varphi}{\partial \ell n p_{co}})^{(0)}_{i_{co},\overline{F}_a} \Delta \ell n p_{co} + (\frac{\partial \ell n\varphi}{\partial \ell n \overline{F}_a})^{(0)}_{i_{co},p_{co}} \Delta \ell n \overline{F}_a; \qquad (20)$$

в) if the explanatory variables are: $i_{co}, p_{co}, \varepsilon_a$:

$$\ell n\varphi = \ell n\varphi^{(0)} + (\frac{\partial \ell n\varphi}{\partial i_{co}})^{(0)}_{p_{co},\varepsilon_a} \Delta i_{co} + (\frac{\partial \ell n\varphi}{\partial \ell n p_{co}})^{(o)}_{i_{co},\varepsilon_a} \Delta \ell n p_{co} + (\frac{\partial \ell n\varphi}{\partial \ell n \varepsilon_a})^{(0)}_{i_{co},p_{co}} \Delta \ell n \varepsilon_a. \qquad (21)$$

Formulas (17) - (21) become simpler if any of diagnostic variables $i_{co}, p_{co}, p_a, \overline{F}_a, \varepsilon$ remains invariable (const).

Thus, for extrapolation of key parameters it is necessary to know their partial derivatives. Values of some from them are computed and placed in tables in an aspect « extrapolation coefficient formulas» $A_1, A_2, B_1, B_2, ..., L_4$. For a presence necessary remaining ones expressions resulted in tab. 2 and tab. 3. are received.

Table 2

	По энтальпии топлива	По давлению в камере сгорания		По параметрам в произвольном сечении сопла	
φ	$\left(\frac{\partial \ln \varphi}{\partial i_{co}}\right)_{p_{co},\rho}$	$\left(\frac{\partial \ln \varphi}{\partial \ln p_{co}}\right)_{i_{co},\rho}$	$\left(\frac{\partial \ln \varphi}{\partial \ln p_{co}}\right)_{i_{co},\varepsilon}$	$\left(\frac{\partial \ln \varphi}{\partial \ln \varepsilon}\right)_{i_{co},p_{co}} = -\left(\frac{\partial \ln \varphi}{\partial \ln \rho}\right)_{s}$	$\left(\frac{\partial \ln \varphi}{\partial \ln F}\right)_{s}$
T	$\frac{1}{c_p T_{co}}$	$-\frac{R_0}{c_p \mu_{co}}$	$\frac{R_0}{c_p \mu}\left(\alpha_p T - \frac{\mu}{\mu_{co}}\right)$	$-\frac{\alpha_p T R_0}{c_p \mu}$	$-\frac{\frac{\alpha_p T R_0}{c_p \mu}}{\frac{\beta_T p}{\varkappa} - \frac{R_0 T}{w^2 \mu}}$
i	$\frac{T}{T_{co}}$	$-\frac{R_0 T}{\mu_{co}}$	$R_0 T\left(\frac{1}{\mu} - \frac{1}{\mu_{co}}\right)$	$-\frac{R_0 T}{\mu}$	$-\frac{\frac{R_0 T}{\mu}}{\frac{\beta_T p}{\varkappa} - \frac{R_0 T}{w^2 \mu}}$
ρ	$-\frac{\alpha_p T}{c_p T_{co}}$	$\frac{\alpha_p T R_0}{c_p \mu_{co}}$	$\frac{\alpha_p T R_0}{c_p \mu_{co}} + \frac{\beta_T p}{\varkappa}$	$-\frac{\beta_T p}{\varkappa}$	$-\frac{\frac{\beta_T p}{\varkappa}}{\frac{\beta_T p}{\mu} - \frac{R_0 T}{w^2 \mu}}$
μ	$\frac{1 - \alpha_p T}{c_p T_{co}}$	$\frac{R_0(\alpha_p T - 1)}{c_p \mu_{co}}$	$\frac{R_0}{c_p \mu}\left(\alpha_p T - \frac{\mu}{\mu_{co}}\right) - {} + \frac{\alpha_p T R_0}{c_p \mu_{co}} + \frac{\beta_T p}{\varkappa} - 1$	$\frac{\alpha_p R_0 T}{c_p \mu}(\alpha_p T - 1) - \beta_T p + 1$	$\frac{\left(\frac{\partial \ln \mu}{\partial \ln \varepsilon}\right)_{i_{co},p_{co}}}{\frac{\beta_T p}{\varkappa} - \frac{R_0 T}{w^2 \mu}}$

Table 3

Таблица 3

	По энтальпии топлива $p_{co}, p = const$	По давлению на входе в сопло $i_{co}, p = const$		По параметрам в произвольном сечении сопла. $i_{co}, p_{co} = const$	
φ	$\left(\frac{\partial \ln \varphi}{\partial i_{co}}\right)_{p_{co},\varepsilon} = \left(\frac{\partial \ln \varphi}{\partial i_{co}}\right)_{p_{co},\rho}$	$\left(\frac{\partial \ln \varphi}{\partial \ln p_{co}}\right)_{i_{co},\rho}$	$\left(\frac{\partial \ln \varphi}{\partial \ln p_{co}}\right)_{i_{co},\varepsilon}$	$\left(\frac{\partial \ln \varphi}{\partial \ln \varepsilon}\right)_{i_{co},p_{co}} = -\left(\frac{\partial \ln \varphi}{\partial \ln \rho}\right)_{s}$	$\left(\frac{\partial \ln \varphi}{\partial \ln \bar{F}}\right)_{s}$
w	$\frac{T_{co} - T}{w^2 T_{co}}$	$\frac{R_0 T}{w^2 \mu_{co}}$	$\frac{R_0 T}{w^2}\left(\frac{1}{\mu_{co}} - \frac{1}{\mu}\right)$	$\frac{R_0 T}{w^2 \mu}$	$\frac{\frac{R_0 T}{w^2 \mu}}{\frac{\beta_T p}{\varkappa} - \frac{R_0 T}{w^2 \mu}}$
f	$\frac{\alpha_p T}{c_p T_{co}} - \frac{T_{co} - T}{w^2 T_{co}}$	$-\left(\frac{\partial \ln w}{\partial \ln p_{co}}\right) - \left(\frac{\partial \ln \rho}{\partial \ln p_{co}}\right)$	$-\left(\frac{\partial \ln w}{\partial \ln p_{co}}\right) - \left(\frac{\partial \ln \rho}{\partial \ln p_{co}}\right)$	$-\left(\frac{\partial \ln w}{\partial \ln \varepsilon}\right) - \left(\frac{\partial \ln \rho}{\partial \ln \varepsilon}\right)$	$\frac{\frac{\partial \ln f}{\partial \ln \varepsilon}}{\frac{\beta_T p}{\varkappa} - \frac{R_0 T}{w^2 \mu}}$
$\bar{F}$	$\frac{\alpha_p T}{c_p T_{co}} - \frac{T_{co} - T}{w^2 T_{co}} - \left(\frac{\alpha_p T}{c_p T_{co}} - \frac{T_{co} - T}{w^2 T_{co}}\right)_*$	$\left(\frac{\partial \ln f}{\partial \ln p_{co}}\right) - \left(\frac{\partial \ln f_*}{\partial \ln p_{co}}\right)$	$\left(\frac{\partial \ln f}{\partial \ln p_{co}}\right) - \left(\frac{\partial \ln f_*}{\partial \ln p_{co}}\right)$	$\left(\frac{\partial \ln f}{\partial \ln \varepsilon}\right)$	1
β	$\frac{\alpha_p T}{c_p T_{co}} - \frac{T_{co} - T}{w^2 T_{co}} - \left(\frac{\alpha_p T}{c_p T_{co}} - \frac{T_{co} - T}{w^2 T_{co}}\right)_*$	—	$1 + \left(\frac{\partial \ln f_*}{\partial \ln p_{co}}\right)$	—	—
I_s^n	$\frac{1}{I_s^n}\left[w\left(\frac{\partial \ln w}{\partial i_{co}}\right) + p f\left(\frac{\partial \ln f}{\partial i_{co}}\right)\right]$	$\frac{1}{I_s^n}\left[w\left(\frac{\partial \ln w}{\partial \ln p_{co}}\right) + p f\left(\frac{\partial \ln f}{\partial \ln p_{co}}\right)\right]$	$\frac{1}{I_s^n}\left\{w\left(\frac{\partial \ln w}{\partial \ln p_{co}}\right) + p f\left[\left(\frac{\partial \ln f}{\partial \ln p_{co}}\right) + 1\right]\right\}$	$\frac{1}{I_s^n}\left\{w\left(\frac{\partial \ln w}{\partial \ln \varepsilon}\right) + p f\left[\frac{\partial \ln f}{\partial \ln \varepsilon} - 1\right]\right\}$	$\frac{\left(\frac{\partial \ln I_s^n}{\partial \ln \varepsilon}\right)}{\frac{\beta_T p}{\varkappa} - \frac{R_0 T}{w^2 \mu}}$