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DETERMINATION METHOD OF OPTIMUM MAIN DESIGN PARAMETERS OF LOX-LH2 EXPANDER-CYCLE LRE FOR REUSABLE OTV (ORBITAL TRANSFER VEHICLE)

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ABSTRACT

In the article the design procedure of optimum main design parameter determinations of LOx-LH2 expander-cycle liquid rocket engine (LRE) for the reusable orbital transfer vehicle (OTV) and mathematical model based on this procedure are considered. The main design parameters in this research are O/F ratio, combustion chamber pressure, nozzle expansion ratio and propellant massflow rate. This mathematical model allows determining optimum main design parameters of Lox-LH2 expander- cycle LRE and its engineering appearances concerning the OTV missions. The main criteria of optimization in this mathematical model are the maximization of payload weight and the minimization of specific cost of payload ascent into target orbit. In order to decide optimum design parameters, following tasks will be solved sequentially: estimation of mass characteristics of construction of LRE and all OTV; estimation of payload weight; cost estimation of development and product of LRE and all OTV; definition of optimum main design parameters of liquid rocket propulsion system and design shape. The estimation of calculation accuracy was carried out by comparison with operated LRE and OTV. This model shows good results with higher accuracy.

ACRONYMS

LRE - liquid rocket engine
OTV - orbital transfer vehicle
LEO - Low Earth orbit
LLO - Low Lunar orbit
GTO - geo-transfer orbit
GEO - geostationary earth orbit

FULL TEXT

Features expander-cycle schemes LRE.

The main feature expander-cycle schemes is absence of the gas generator for creation of a propulsive mass of turbine. It gives this scheme, both advantages, and lacks in comparison with the classic closed scheme. In Fig. 1 the typical scheme expander-cycle LRE is represented.

Advantages of the given scheme are [1,2,3,4]:

- higher reliability level due to low temperature (nearby 300 K) a propulsive mass (hydrogen) in inlet of turbines, absence of such heat-stressed aggregate as the gas generator, exceptions of overtemperatures at start, shutdown and failures of the supply system;
- smaller weight LRE due to absence of the gas generator, aggregates and the reinforcement which were ensuring the functioning it;
- a capability of a lot of starts LRE in conditions of space because of absence vapor of waters in cavities turbopumps, and, hence, and exceptions of cases of their freezing before repeated actuation;
- the simplified scheme of start;
- greater resource turbopump;
- reduction of costs of a hardware by development;
- reduction of cost of manufacture;
- reduction of time spent for development and achievements of demanded reliability level;

Lacks expander-cycle schemes:

- a greater starting duration and an reach on a nominal mode of thrust;
- the capability of increase of specific parameters of the engine due to a pressure increase in the combustion chamber because of complexity of obtaining of a heat of the chiller (hydrogen) in jacket of combustion chamber is limited.

In table 1 basic performances modern LRE expander-cycle schemes are presented.

The concept of a method and mathematical model constructed on its basis.

In a conventional practice of an engine building designing is based on properties LRE as thermal machine. However, at the present stage of intensive development spacecrafts such approach is insufficient for full satisfaction to target problems of the ascent with high quality. It speaks that, first, LRE for spacecrafts is first of all an actuator of a control system, and secondly, LRE represents the complicated onboard complex of spacecraft closely cooperating with other systems of spacecraft.

The problem of designing optimum LOx-LH2 expander-cycle LRE for expandable and reusable OTV assumes the ultimate goal:

- determination and justification of main design parameters LRE proceeding from the purposes and the optimum solution of tasks of control OTV;
- determination of an optimum design shape and optimum parameters of subsystems of OTV propulsion system;
- determination of optimum parameters of elements of subsystems of OTV propulsion system.

The term "optimum" in this case reflects purposefulness of a selection of the main values and the parameters describing them, fulfilment of problems of control OTV proceeding directly from requirements with maximum efficiency and quality, and simultaneously, interaction LRE adequating to demanded conditions with others onboard systems.

Practically the designer of complex systems never manages to reduce the problem to cleanly mathematical problem of optimization of criterion at known limitations. Designing LRE of OTV is, as a rule, the iterative process connected with series improvement of system, acceptance of design solutions. Each cycle includes the analysis of efficiency of a product, influence on it of characteristics of individual systems and limitations.

The knowledge of structure LRE of OTV, the program of operation and characteristics of its elements enables to construct criterion function

$$K = f(\bar{a}, \bar{x}, \bar{m}) \qquad (1)$$

where $\bar{a}$ - vector of constant characteristics of systems; $\bar{x}$ - vector of chosen design parameters; $\bar{m}$ - vector of limitations.

Optimum design parameters correspond to an extremum of criterion function. By means of simple iterative methods it is possible to find an extremum of the criterion function easily enough. However, application of iterative mathematical methods of series improvement of systems not always conveniently as they possess a number of lacks. Not always criterion function is differentiated on all variables, and, hence, and to find a global extremum it is not obviously possible. Engineering problems of optimization in the essence multicriteria and their nature is those, that with improvement of one criteria of quality others worsen.

In this method as criteria of optimization of main design parameters LRE of OTV (expandable and reusable) – the maximum weight of a payload and minimal specific cost of the launch to the target orbit.

For detection of a degree of influence of each parameter LRE of OTV on the chosen criteria and solutions of the designing problems creation of mathematical model considering following factors is necessary:

1. Value of required characteristic velocity of the orbital transfer for the ascent of a payload, i.e. energy consumption of a typical solved orbit transfer problem.
2. The expected total payload traffic for all time of implementation of the program of transportation use created OTV.
3. Weight OTV in an initial orbit.
4. Reuse rate of OTV for all term of operation.
5. Reliability LRE OTV.
6. Features of the scheme functioning and the fuel used in LRE of OTV.

The purpose of this method is the creation of the mathematical model for obtaining set main parameters of LRE corresponding minimal specific costs of the ascent and the maximal weight of a payload injected into a target orbit. But, besides the solution of a problem of optimization main parameters of LRE by the chosen criteria, the mathematical model should consider a realizability of received values of main parameters of LRE in the real engine and to assess design parameters of propulsion system units for the analysis their by expert and making of design solutions for their creation. For this purpose in model the module of check of received values main parameters of LRE on a realizability contains. Check implements by definition of balance of powers of pumps and turbines of the engine. For this purpose on main parameters of LRE (such as combustion-chamber pressure, massflow, expansion ratio of the nozzle and O/F ratio calculate expected parameters of its units. Such as:

- inlet pressure in boost pumps;
- inlet pressure in the main pumps;
-optimum frequency of rotation of boost pumps shaft and main pumps for the set charges corresponding the maximal efficiency of pumps;
- efficiency of turbines;
- efficiency of boost pumps and main pumps;
- outlet pressure from the main pumps;

Estimating a realizability of received set main parameters of LRE the expert can change borders of search of optimum design parameters and find the best solutions. After check on a realizability the expert analyses the received results and develops technical shape propulsion system of LRE, or develops the design solution on modernization already existing LRE or continues search main parameters of LRE in view of limitations on a realizability.

Let's consider more in detail structure of mathematical model .

Structure of mathematical model

As the initial data in model following parametres are accepted:

- characteristic speed of interorbital transition;
- height of an initial orbit;
- initial weight OTV in a low orbit;

This initial data changeable and them is necessary for setting before calculation carrying out. Optimized main parameters of LRE are:

- O/F ratio;
- pressure in the combustion chamber;
- nozzle expansion ratio;
- massflow rate;
- probability of non-failure operation LRE at each ignition;
- total fire resource LRE for all time of operation;
- total quantity of ignitions LRE for all time of operation.

Program realization of method allows to create interrelations between modules by a principle «everyone with everyone». This principle of interrelation allows to reconstruct easily model, for the solution of concrete special problems applying only necessary modules. In Fig. 2 the data transmission structure between program modules is shown.

In the developed model calculation of optimum main design parameters of LRE is made in some stages.

At the first stage the expert, being set by the initial data, calculate optimum values of pressure in the combustion chamber, the massflow rate, nozzle expansion ratio and O/F ratio by criterion of the maximum weight of a payload. He sets a range of a variation of these parameters, being guided by statistics of already created expander-cycle LRE, but with overestimate on 30 %.

At the second stage, with optimum values of pressure in the combustion chamber, the massflow rate, nozzle expansion ratio and O/F ratio, check on a realizability in LRE of the received parameters by means of the corresponding module is made. As a result of work of this module calculation main design parameters of LRE of units of feeding system of LRE also is made.

Further, at the third stage check a condition of performance of balance of power if with the given set of parametres (pressure in the combustion chamber, the massflow rate, nozzle expansion ratio and O/F ratio) is impossible to receive the balance of power of pumps and turbines return to the first stage is made and limits of a variation of pressure in the combustion chamber are corrected towards reduction of the top border, as the scheme of expander-cycle LRE the closed. Correction is made before reception of balance of powers with necessary accuracy. If the balance of powers converges, return to the first stage also is made, but borders of a variation of pressure in the combustion chamber are corrected towards increase in the top border. Correction is made to a finding of the greatest possible value of pressure in the combustion chamber.

At the fourth stage received main design parameters of LRE arrive in the module of calculation optimum main design parameters of LRE by criterion minimum specific costs to the ascent into a target orbit. Result of work of the given module is reception of optimum values – probabilities of non-failure operation LRE at each ignition, total fire resource LRE for all time of operation and total quantity of ignition LRE for all time of operation. Thus, the full set of optimum design parameters LRE for expandable or reusable OTV is calculated. Taking into account calculated values main design parameters of units feeding systems of LRE, the expert can finish technical shape of LRE.

In this method, for calculation of weights of tanks and all feeding system LRE, design OTV and weights of a payload are used methods developed in Moscow Aviation Institute on Department 202 “Rocket engines” and based on statistics created LRE for last 50 years.

Calculation in the module of weight LRE is conducted by a technique given developed in Moscow Aviation institute [13], but with correction of approximation factors on statistics known on the present moment of weights really existing LRE. In detail essence of changes initial relations is stated in [14].

Initial data for calculation are: α, p_κ, $\overline{F}$ and G_s. Output data are - weights boost turbopump of fuel and an oxidizer, turbopump fuel and an oxidizer, weight of the combustion chamber, weight of the nozzle, weight of a frame of the engine and other elements. Also in this module the real specific impulse of LRE calculates. This parameter is used at calculation of weight LRE, and also it participates in calculations in other modules. Calculation of specific impulse LRE is conducted in two stages. At the first stage under the interpolated data of thermodynamic calculations. calculation of ideal specific impulse is made on α, p_κ, $\overline{F}$ and G_s [15]. At the second stage set α, p_κ, $\overline{F}$ also G_s losses of specific impulse in the nozzle are determined. Receiving losses in the combustion chamber equal φ_c=0,995 , there is a factor of loss of specific impulse φ_{Isp} $\varphi_c \cdot \varphi_{nozzle}$ as product of a loss coefficient in the combustion chamber on a loss coefficient in the nozzle, and further is the real value of specific impulse. [16]

In Fig. 3 is shown the chart of concurrence of results of calculation of the values of weights LRE with real.

Module of calculation of weight of design OTV.

During calculation of weight of design OTV (or "dry" weight OTV) consistently calculate, and weights - a fuel bay, weight of the RCS, an instrument module and other systems are then summarized. And also to this sum weight LRE found earlier adds. The weight of fuel is calculated on value of characteristic velocity of inter-orbital transition, altitude of an initial orbit, weight LRE in an initial orbit, O/F ratio, combustion-chamber pressure, nozzle expansion ratio and the massflow rate in the combustion chamber In Fig. 4 chart of comparison of the calculated values of weights of designs OTV with real weights of designs OTV taken from mass media is shown.

In Table 3 characteristics OTV for which calculation of weights of designs for an estimation of adequacy of model has been executed are shown. The weight of fuel was calculated for two-impulse Homan inter-orbital transition on values of characteristic velocities taken from mass media.

Module of calculation of weight of a payload injected MTA into a target orbit.

During calculation such parameters as weight LRE, weight of a fuel bay, weight of an instrument module, weight of other systems are used. Initial data for calculation are: value of characteristic velocity of inter-orbital transition, altitude of an initial orbit, weight OTV in an initial orbit, O/F ratio, combustion-chamber pressure, nozzle expansion ratio and a massflow propellant in the combustion chamber. [16]

Calculation of cost of development, manufacture LRE and OTV, the ascent of a payload is made by a TRANSCOST 7.2 by Dietrich Koelle.

Search of optimum main design parameters of LRE is made with use of method Parameter Space Investigation method (PSI) developed in Institute IMASH the Russian academy of sciences.

In Fig. 5 is shown the chart of concurrence of results of calculation of the values of weight of payload OTV with real.

In Fig. 6 and 7 examples of calculation of units of the feeding system of some real LRE are shown.

Example of calculation main design parameters of LRE for OTV.

In table 4 results of calculation main design parameters of LRE for expandable OTV are shown. Calculation is made for expandable OTV making inter-orbital transition to various orbits and LRE having various diameter (d_a) of the nozzle. Specific velocity of orbital transfer for GEO is 4800 km/sec, for GTO is 2500 km/sec, to the Moon is 3500 km/sec.

In the presented data it is visible that the increase in expansion ratio of the nozzle allows to increase weight of a payload and to reduce specific cost of the ascent. But for the ascent of a payload on GTO increase in weight not considerably in percentage terms. At increase in diameter of the nozzle for LRE for OTV transferred a payload on GEO also weight LRE increases and the thrust to weight ratio is reduced that conducts to reduction in weight of a payload. Therefore in this case optimum the value of thrust increases.

In table 5 results of calculation main design parameters of LRE for reusable OTV are shown. Calculation is made for reusable OTV making inter-orbital transition to various orbits and LRE having various diameter (d_a) of the nozzle and OTV having various initial weight on LEO. Specific velocity of orbital transfer for GTO (from Baikonur) is 3200 km/sec, for LLO is 4200 km/sec.

In the presented data we may see that for specific velocity of orbital transfer 3200 km/sec, the increase in diameter of the nozzle up to 4 m for LRE for reusable OTV transporting payload on GTO and having weight 24500 kg reduces weight of a payload because the increase in weight of the nozzle is not compensated by increase in specific impulse. For weight 50000 kg the increase in expansion ratio of the nozzle allows to increase weight of a payload, but increase the specific cost of the ascent. Because the increase in weight of payload does not compensate increase in cost of manufacture of heavier LRE and OTV as a whole. But we may see that for weight 95000 kg the increase in expansion ratio of the nozzle allows to increase weight of a payload and to reduce specific cost of the ascent.

For specific velocity of orbital transfer 4200 km/sec and initial weight on LEO 24500 kg obtained data do not represent practical interest. For other weights (50000 kg and 95000 kg) obtained data have the same character as for expandable LRE.

Optimum O/F ratio for reusable LRE is higher in comparison with expandable LRE because for the ascent of the maximal weight of a payload propellant of higher density is required.

Optimum chamber pressure for OTV with weight 24500 kg and nozzle diameter 4 m is between 50 and 60 atm because the increase pressure in the chamber leads to increase of pressure in outlet pumps and to increase in weight turbopumps and the engine as a whole.

Conclusion

The method considered in the this article and realized on the basis of it mathematical model allows to receive great volume of data for the analysis and discussions at designing expander-cycle LRE of various purpose.

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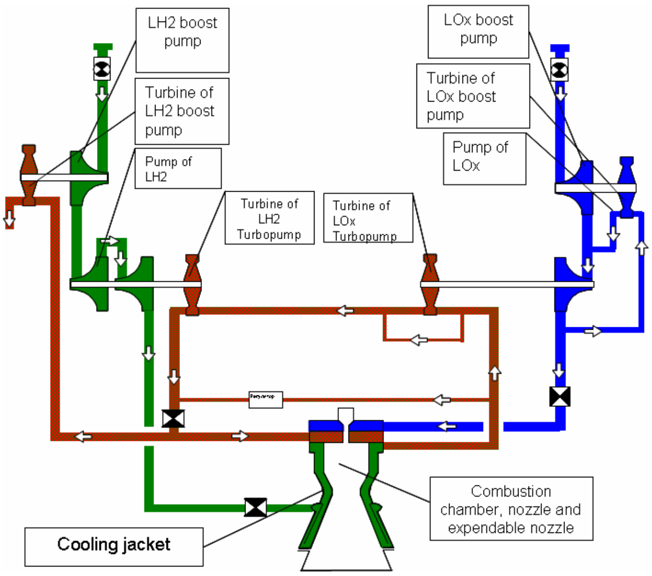


Figure1. Typical scheme of expander-cycle LRE [1,2,3,4]

Table 1. Basic performances modern LRE expander-cycle schemes [1, 5,6,7,8,10,11,12]

Country	LRE	Thrust, kN	Sp. impulse, m/s	Km	Chamber pressure, MPa	Nozzle expansion ratio	Weight, kg
Japan (Mitsubishi)	LE-5B	137	4404	5	3,63	110:1	269
USA (Pratt and Whitney)	RL-10A-4-2	99	4424	5,5	4,3	130:1	210
USA (Pratt and Whitney)	RL-10B-2	110	4547	5,85	4,5	285:1	308
USA (Boeing)	MB-60	267	4581	5,8	13,4	300:1	591
Russia (KBKhA)	РД-0146	98,1	4542	5,9	8,08	210:1	260
USA (Pratt and Whitney)	RL-60	267	4561	5,85	8	200:1	498
EU (EADS)	Vinci	180	4561	5,85	6,08	240:1	450

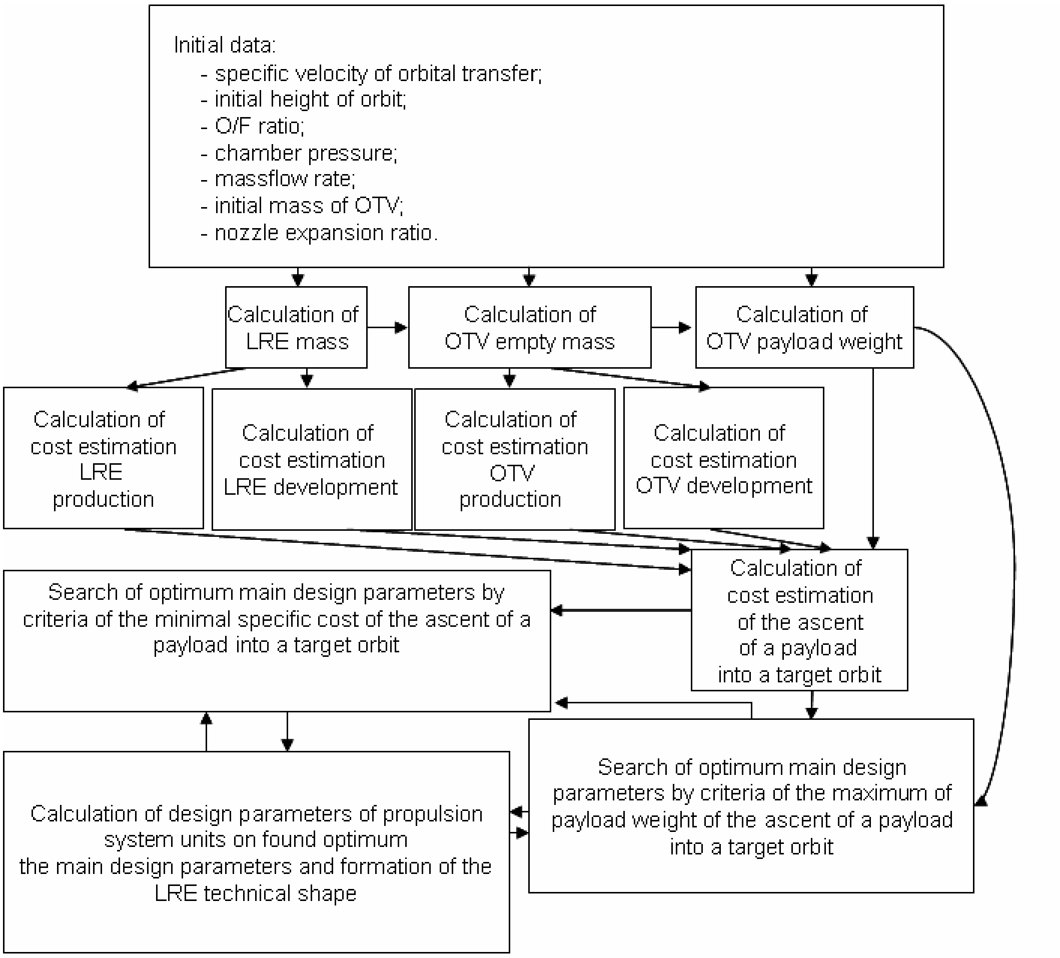


Figure 2. Structure of mathematical model of search of optimum main parameters of LRE of reusable OTV by criteria of the minimal specific cost and the maximal weight of a payload transferred to a target orbit.

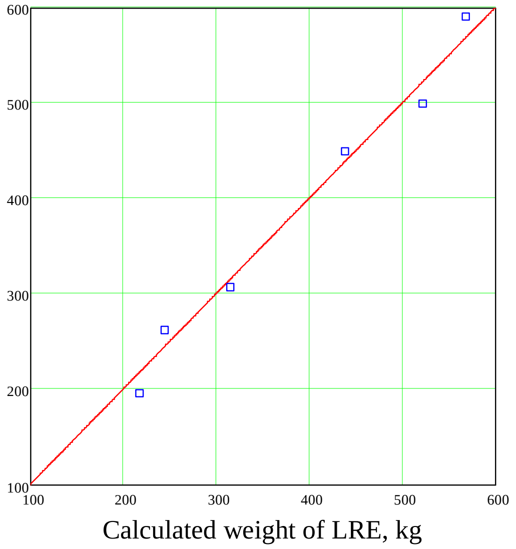
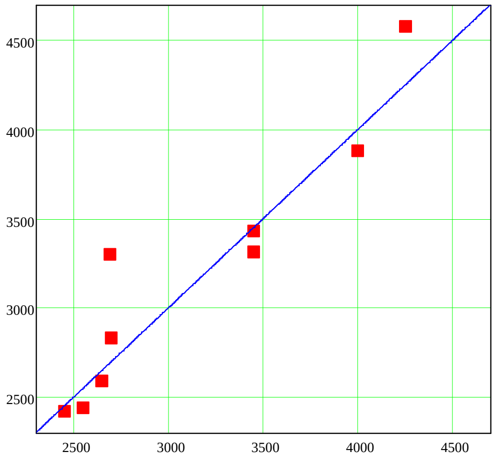


Figure 3. Comparison of calculated weights LRE presented to table 1 with real values.

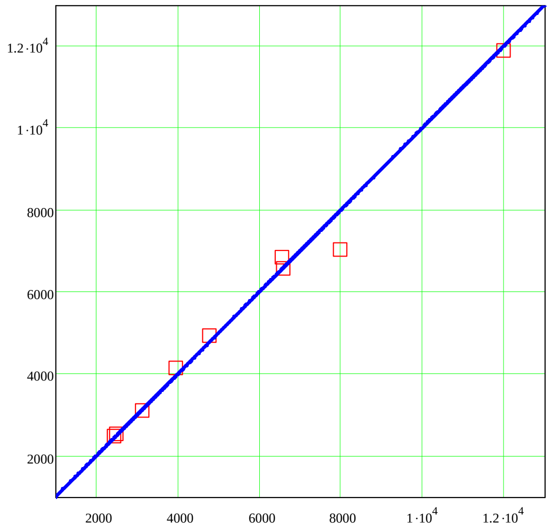
Table 2. Main design parameters modern LRE expander-cycle schemes which weights are calculated and presented in Fig 2. [1, 5,6,7,8,10,11,12]

Country	LRE	Thrust, kN	Sp. impulse, m/s	Km	Chamber pressure, MPa	OTV	Nozzle expansion ratio	Weight LRE, kg
USA (Pratt and Whitney)	RL-10A-4-2	99	4424	5,5	4,3	Centaur	120:1	230
USA (Pratt and Whitney)	RL-10B-2	110	4532	5,85	4,5	Delta-4 - Centaur	285:1	308
USA (Boeing)	MB-60	267	4532	5,8	13,4	Centaur	300:1	591
Russia (KBKhA)	РД-0146	98,1	4542	5,9	8,08	КВРБ	210:1	260
USA (Pratt and Whitney)	RL-60	267	4561	5,85	8	Centaur	200:1	500
EU (EADS)	Vinci	180	4561	5,85	6,08	Vinci	240:1	450



Weights of designs OTV calculated, kg

Figure 4. Comparison of weights of design OTV calculated on model with real.



Weight of payload, real

Figure 5. Comparison of weights of the payload transferred by OTV into a target orbit, calculated on model with real.

Table 3. Weights of designs modern MTA and characteristics of their sustainers

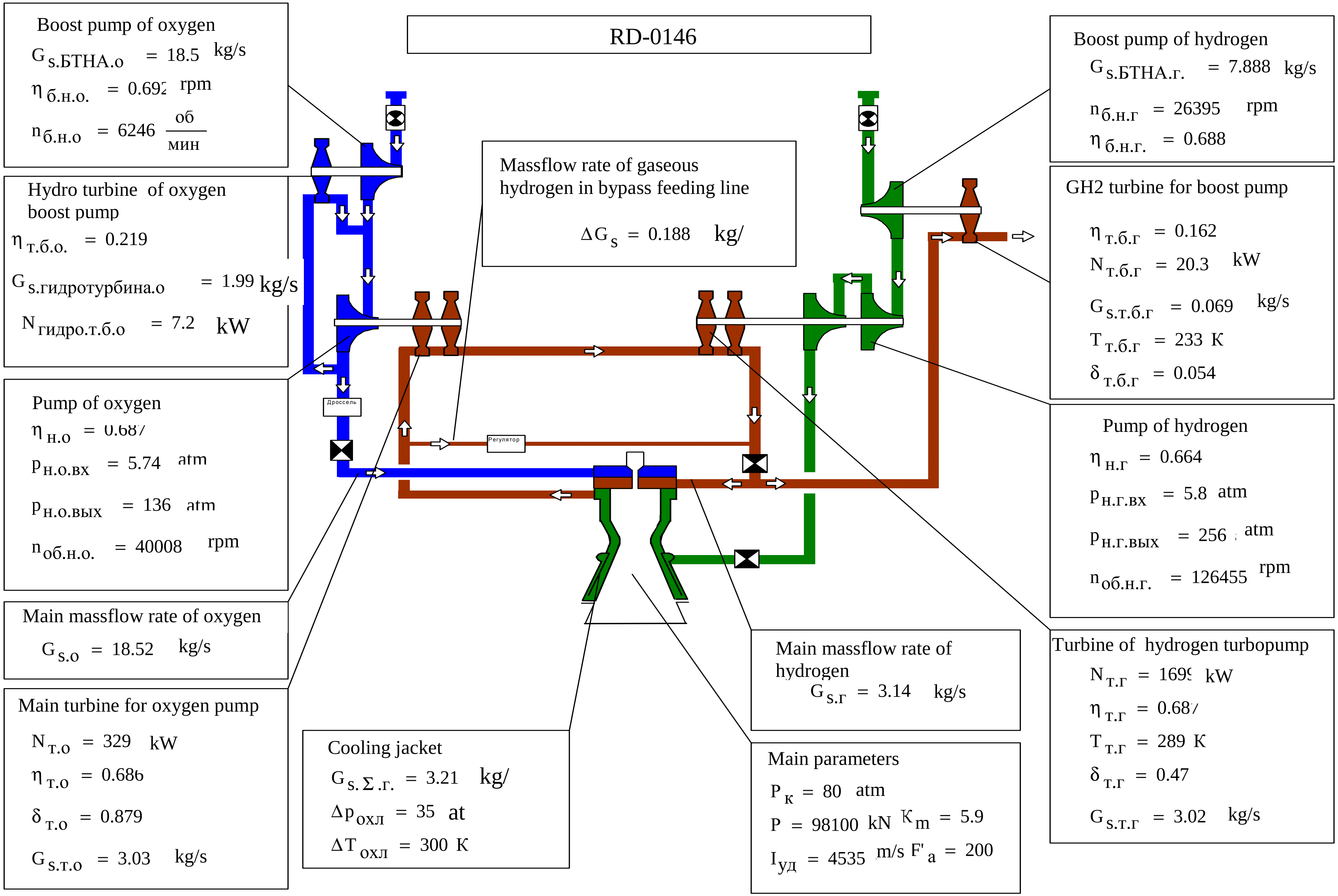
OTV	Main LRE	Characteristic velocity for the ascent into a target orbit, m/s	Weight of a payload delivered into a target orbit, kg	Weight OTV in an initial orbit, kg	Weight of fuel OTV, kg	Weight of design OTV, kg
12КРБ (Russia)	KVD-1M	4800	4512	5,7	11200	2450
KVRB (Russia)	KVD-1M	3650	4512	5,7	15200	2700
Storm (USSR)	RD-56	4920	4388	5,7	12600	2650
H10-3 Ariane 4 (EU)	HM-7B	3540	4370	3,7	10820	2550
ESC-A Ariane 5 (EU)	HM-7B	3260	4370	3,7	14510	2690
ESC-B Ariane 5 (EU)	Vinci	4110	4561	6,08	29440	4250
Atlas5-Centaur (USA)	RL-10A-4-2	4880	4424	4,3	20085	3450
Delta-4M - Centaur (USA)	RL-10B-2	5480	4532	4,5	20050	3450
Delta-4M - Centaur (USA)	RL-10B-2	4480	4532	4,5	26430	4000

Mass OTV on LEO, kg	Specific velocity of orbital transfer, km/sec	Reliability goal of LRE	Specific cost of payload weight, $/кг	Payload Weight, kg	O/F ratio	Nozzle expansion ratio	Chamber pressure, MPa	Massflow rate, kg/sec	Specific impulse, m/sec	Thrust (in vac), kN	Overall time of work, sec
(d_a=1.2м)											
24500	4800	0.973	21320	4929	5.9	380	8.235	46,69	4446	207.6	352.8
24500	3500	0.963	13530	8080	5.87	98	8.25	41.44	4461	184.9	327.5
24500	2500	0.947	10070	11230	5.84	117	8.276	33.612	4481	137.2	318
(d_a=2.2м)											
24500	4800	0.973	18700	4606	6.5	265	8.04	52,05	4528	235	302.4
24500	3500	0.967	13360	8231	5.99	303	8.153	44.89	4565	205	327.5
24500	2500	0.947	10070	11350	5.98	380	8.245	37.22	4581	170.5	281

Table 4. Optimum main design parameters of LRE for expandable LRE.

Mass reus. OTV on LEO, kg	Specific velocity of orbital transfer, km/sec	Reliability goal of LRE	Specific cost of payload weight, $/кг	Payload weight, kg	O/F ratio	Nozzle expan. ratio	Chamber pressure, MPa	Massflow rate, kg/sec	Specific impulse, m/sec	Thrust (in vac), kN	Quantity of restarts for one engine	Overall time of work, sec
d_a= 2.2 m (Total payload traffic for whole transportation program 720000 kg)												
24500	3200	0.915	16930	5534	7.1	341	7.457	36.741	4533	167	70	24640
50000	3200	0.921	13710	14520	6.73	174	8.16	76.4	4461	185	28	9156
95000	3200	0.918	12710	29250	6.55	117	8.9	131.845	4481	137	15	4770
24500	4200	0.909	15090	521	7.11	295	7.55	44.2	4523	200	604	206272
50000	4200	0.921	33870	5061	7.12	161	8.1	84.5	4460	376	77	28400
95000	4200	0.918	28780	10960	7.24	119	8.75	131	4414	580	36	16500
d_a= 4 m (Total payload traffic for whole transportation program 720000 kg)												
24500	3200	0.915	17350	5388	6.85	694	5.856	44.82	4589	206	72	21744
50000	3200	0.921	13740	14670	7.08	605	7.89	77.5	4565	205	27	8829
95000	3200	0.918	12480	30040	7.04	384	8.6	137	4581	170.5	14	3934
24500	4200	0.909	24640	309	6.97	594	5.192	50.48	4573	231	2064	610544
50000	4200	0.916	32320	5327	7.24	423	7.67	88.7	4550	403	73	25280
95000	4200	0.918	25630	12460	7.16	292	8.7	164	4526	742	32	11430

Table 5. Optimum main design parameters of LRE for reusable OTV



RD-0146

Boost pump of oxygen

$G_{\text{s.БТНА.о}} = 18.5$ kg/s

$\eta_{\text{б.н.о.}} = 0.692$ rpm

$n_{\text{б.н.о}} = 6246 \ \frac{\text{об}}{\text{мин}}$

Hydro turbine of oxygen boost pump

$\eta_{\text{т.б.о.}} = 0.219$

$G_{\text{s.гидротурбина.о}} = 1.99$ kg/s

$N_{\text{гидро.т.б.о}} = 7.2$ kW

Pump of oxygen

$\eta_{\text{н.о}} = 0.687$

$p_{\text{н.о.вх}} = 5.74$ atm

$p_{\text{н.о.вых}} = 136$ atm

$n_{\text{об.н.о.}} = 40008$ rpm

Main massflow rate of oxygen

$G_{\text{s.о}} = 18.52$ kg/s

Main turbine for oxygen pump

$N_{\text{т.о}} = 329$ kW

$\eta_{\text{т.о}} = 0.686$

$\delta_{\text{т.о}} = 0.879$

$G_{\text{s.т.о}} = 3.03$ kg/s

Massflow rate of gaseous hydrogen in bypass feeding line

$\Delta G_{\text{s}} = 0.188$ kg/

Cooling jacket

$G_{\text{s.}\Sigma\text{.г.}} = 3.21$ kg/

$\Delta p_{\text{охл}} = 35$ at

$\Delta T_{\text{охл}} = 300$ К

Main massflow rate of hydrogen

$G_{\text{s.г}} = 3.14$ kg/s

Main parameters

$P_{\text{к}} = 80$ atm

$P = 98100$ kN $K_m = 5.9$

$I_{\text{уд}} = 4535$ m/s $F'_a = 200$

Boost pump of hydrogen

$G_{\text{s.БТНА.г.}} = 7.888$ kg/s

$n_{\text{б.н.г}} = 26395$ rpm

$\eta_{\text{б.н.г.}} = 0.688$

GH2 turbine for boost pump

$\eta_{\text{т.б.г}} = 0.162$

$N_{\text{т.б.г}} = 20.3$ kW

$G_{\text{s.т.б.г}} = 0.069$ kg/s

$T_{\text{т.б.г}} = 233$ К

$\delta_{\text{т.б.г}} = 0.054$

Pump of hydrogen

$\eta_{\text{н.г}} = 0.664$

$p_{\text{н.г.вх}} = 5.8$ atm

$p_{\text{н.г.вых}} = 256$ atm

$n_{\text{об.н.г.}} = 126455$ rpm

Turbine of hydrogen turbopump

$N_{\text{т.г}} = 1699$ kW

$\eta_{\text{т.г}} = 0.687$

$T_{\text{т.г}} = 289$ К

$\delta_{\text{т.г}} = 0.47$

$G_{\text{s.т.г}} = 3.02$ kg/s

Figure 6. Example of calculation of parameters of units of feeding system for LRE (type RD-0146).

Vinci

Boost pump of hydrogen

$n_{\text{б.н.г}} = 20181$ rpm

$G_{\text{s.б.н.г.}} = 5.92$ kg/s

$\eta_{\text{б.н.г.}} = 0.69$

Turbine of hydrogen boost

$N_{\text{т.б.г}} = 30$ kW

$\delta_{\text{т.б.г}} = 0.084$

$\eta_{\text{т.г.б}} = 0.18$

$G_{\text{s.г.т.б.}} = 0.115$ kg/s

$T_{\text{т.б}} = 201$ K

Hydrogen pump

$\eta_{\text{н.г}} = 0.677$

$p_{\text{н.г.вх}} = 5.8$ atm

$P_{\text{н.г.вых}} = 179.7$ atm

$n_{\text{об.н.г}} = 81289$ rpm

Turbine of hydrogen pump

$G_{\text{s.т.г}} = 5.86$ kg/s

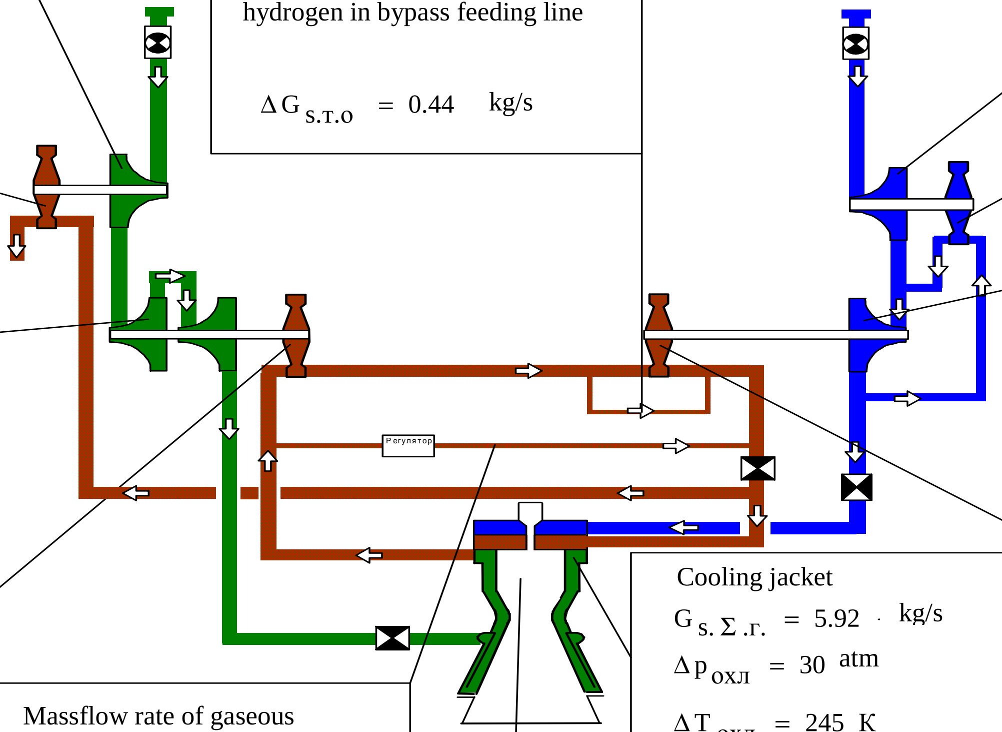
$\delta_{\text{т.г}} = 0.55$

$\eta_{\text{т.г}} = 0.654$

$N_{\text{т.г}} = 2142$ kW

Massflow rate of gaseous hydrogen in bypass feeding line

$\Delta G_{\text{s.т.о}} = 0.44$ kg/s



Massflow rate of gaseous hydrogen in bypass feeding line

$\Delta G_{s} = 0.06$ kg/s

Boost pump of oxygen

$n_{\text{б.н.о}} = 4634$ rpm

$\eta_{\text{б.н.о}} = 0.692$

$G_{\text{s.б.н.о}} = 33.7$ kg/s

Hydro turbine of oxygen boost pump

$\eta_{\text{т.б.о.}} = 0.27$

$N_{\text{г.т.б.о.}} = 13$ kW

$G_{\text{s.т.б.о}} = 3.5$ kg/s

Oxygen pump

$\eta_{\text{н.о}} = 0.687$

$n_{\text{об.н.о}} = 21470$ rpm

$p_{\text{н.о.вх}} = 5.7$ atm

$P_{\text{н.о.вых}} = 91$ atm

$G_{\text{s.н.о}} = 37.2$ kg/s

Turbine of oxygen pump

$\delta_{\text{т.о}} = 0.843$

$\eta_{\text{т.о}} = 0.602$

$T_{\text{т.о}} = 207$ K

$N_{\text{т.о}} = 405$ kW

$G_{\text{s.т.о}} = 5.417$ kg/s

Cooling jacket

$G_{\text{s.}\Sigma\text{.г.}} = 5.92$ kg/s

$\Delta p_{\text{охл}} = 30$ atm

$\Delta T_{\text{охл}} = 245$ K

Main parameters

$P_{\text{к}} = 60.8$ atm

$K_{m} = 5.8$

$I_{\text{уд}} = 4560$ m/s

$F'_{a} = 240$

$P = 180$ kN

Figure 7. Example of calculation of parameters of units of feeding system for LRE (type VInci).