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THE CONCEPT FOR LIQUID ROCKET ENGINE SYSTEM DESIGN

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ABSTRACT

This paper represents the concept for computer-aided liquid rocket engine system (LRES) design. In order to reduce the computational load on the computer, the computational scheme of LRES is divided into five main modules, which themselves consist of various submodules. At the same time, within the framework of each module, design of individual submodules is carried out. This allows to reduce the number of residuals and avoid conflicts between the modules. Sequentially parallel design of modules and submodules allows to reduce the dimension of the system of nonlinear algebraic equations to compute the energy balance of LRES. Currently is being developed WEB-based software based on the proposed approach for LRES design.

INTRODUCTION

As known, LRES design, as a complex technical system, is a time-consuming, hierarchically multiphase and iterative process. This process is carried out by cyclic repetitions and returns to the previous design phases. At the same time in the technical specifications (technical requirements) for LRES design the following elements should be indicated: specific thrust (or specific impulse); thrust control range; control algorithm or program of LRES operation - Thrust=f(Time); full running time; engine start multiplicity; nature of thrust variation on transient conditions at start; regulation and shutdown of LRES; rocket flight trajectory; propellant components; total impulse and after-effect impulse; maximum allowable engine weight and its dimensions; reliability; conditions for rocket control by engine (turning thrust chamber, gas rudders, etc.), requirements for manufacturing technologies; economy; ecology; LRES operating conditions; as well as a number of other requirements that reflect the specifics of the rocket operation [Kozlov et al., 1988; Gakhun et al., 1989]. The development of the LRE is a separate process in the context of designing the entire flight vehicle (rocket-carrier, missile, etc.), which general scheme is shown in the paper Abdullayev and Abdulla (2019).

The laborious, multi-phase and iterative nature of LRES design determines the use of a multidisciplinary approach using modern computer technologies. Until now, various systems of computerized LRES design have been developed, each of which is characterized by its own advantages and disadvantages.

As an example, we can consider such systems - CEA (NASA, USA), CET93 and CETPC (NASA, USA), SCORES (SpaceWorks, USA), Astra.4/pc, TERRA (MSTU named after

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N.E.Bauman, Russia), RPA (Germany), ANASYN (Keldysh Research Center, Russia), LRES (Yuzhnoye Design Office, Ukraine), REDTOP PRO (SpaceWorks, USA), EcosimPRO PROOSIS (Empresarios Agrupados Internacional S.A., Spain), EcoSimPRO&ESPSS(ESA, EU), LPR2/SEQ (German Aerospace Center- DLR), LIRA (Delft University of Technology, Netherlands) etc.).

Many of these design systems are based on object-oriented programming and use of the Newton-Raphson and Runge-Kutta solvers [Bel and Sanchez, 2001; Steelant et al., 2010; Vazquez et al., 2010; Lebedinsky et al., 2009; Sydorenko and Nikishchenko, 2015; Petzold, 1983]. Despite their widespread use, there are problems that are related both to the organizational structure and their mathematical tools.

As known, development of a new propulsion system is a synthesis process on the complete consistency of all variables of generated LRES network. The synthesis of a new LRES consists of several stages [Vasiliev et al., 1983; Vazquez et al., 2010; Naderi et al., 2017; Lebedinsky et al., 2009; Sydorenko and Nikishchenko, 2015]:

1) Forming the pneumohydraulic scheme of LRES,

2) Setting the input data (the efficiency of pumps and turbines, estimated pressure drops in the pipelines and engine units, the required thrust, the mixture ratio of fuel components, etc. at the nominal mode),

3) Forming the system of equations for LRES network,

4) Solving the system of equations of the LRES network.

However, the problem of forming an optimal system of equations and the choice of effective input data, including constraints, remains unresolved. The analysis of existing studies show that the development of such LRES design systems does not take into account the property of its mixed hierarchical structure. Summarizing the existing experience, in this paper have been offered recommendations for formation and solution of the system of equations for LRES network. Development of a mathematical model is necessary in the synthesis of LRES to maintain balanced relationship between its variables.

In this paper for the synthesis of a LRES, a static model is used (when liquid and gas flows at constant speeds, the rotational speed of the shafts of turbines and pumps is constant, there are no gas and liquid containers). With this approach, LRES is a pneumo-hydraulic network that can be described by a nonlinear system of algebraic equations.

PRINCIPLES FOR DEVELOPMENT OF LRES MATHEMATICAL MODEL

Since LRES is a rather complex system, its mathematical model is traditionally built according to the aggregation principle. In accordance with this principle, LRES general model is composed of separate, simpler and autonomous components (blocks). Each component represents models with equations, variables, data, etc.. All components are connected into one common network (Fig. 1). A set of mathematical models combined into a common system represents the mathematical model of LRES network. Thanks to this approach, step-by-step LRES design is carried out. In this case, all LRES components must have input and (or) output ports that ensure the interaction of the other components with the network. The component port contains a vector of lumped variables for making a system of equations (Table 1). Values for variables can be generated based on both the calculation results of the previous LRES module and the data (boundary conditions, constrains), which are given by the user from a specific interval based on existing design experience and experiments. Ports are classified according to the physical nature of the processes: hydraulic, gas and mechanical, etc. Determination the optimal list of ports' variables and constraints allows to form and solve a system of equations correctly. For example, temperature is a function of enthalpy and pressure, and density is a function of temperature and pressure [Lebedinsky et al., 2009; Vasiliev et al., 1983; Goertz, 1995; Sydorenko and Nikishchenko, 2015].

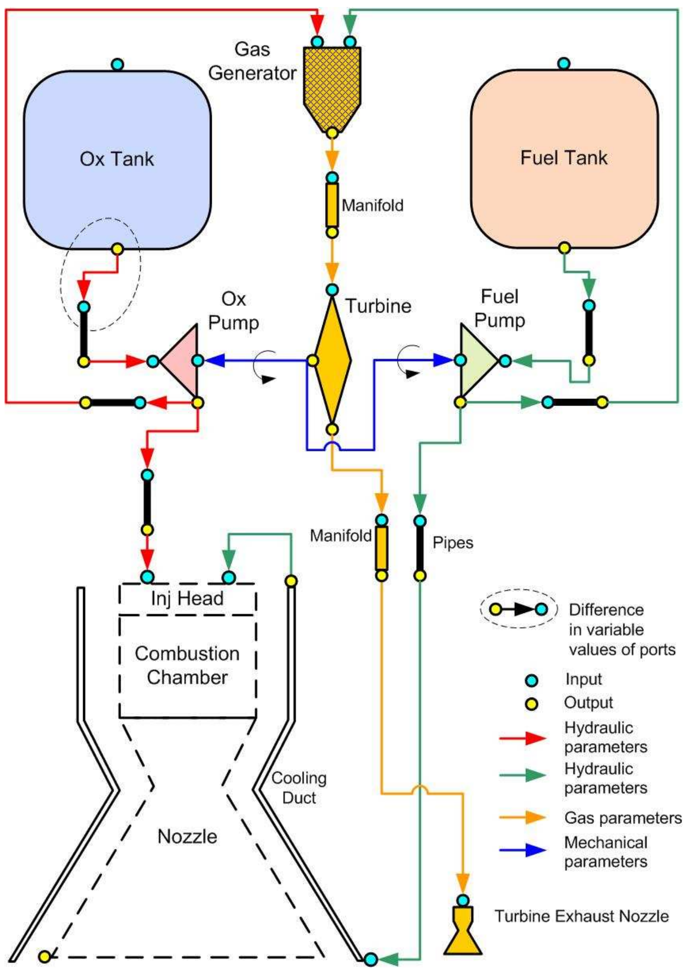

Figure 1. LRES Computation Scheme Without Afterburning Gas Generator

Table 1. Variables for Components Ports

№	Designation	Description
Hydraulic ports		
1	p	Pressure
2	H	Enthalpy
3	$\dot{m}$	Mass flow rate
Gas ports		
1	p	Pressure
2	H	Enthalpy
3	$\dot{m}$	Mass flow rate
4	R	Gas constant
5	γ	Isentropic exponent
6	K_m	Mixture ratio
Mechanical ports		
1	N	Power
2	n	Rotation frequency

HIERARCHICAL STRUCTURE OF LRES DESIGN SYSTEM

In order to create an effective LRES design system, its hierarchical structure should be formed. Analysis of the existing design systems for LRES show that above listed design systems are practically based on a unidirectional hierarchical structure [Gakhun et al., 1989]. LRES design system is based on the top-down design (descending design). Here LRES is considered as a part of the rocket propulsion system, the structure of which is shown in Fig. 2. As observed LRES elements and subsystems are distributed over four levels of hierarchy. Therefore, initial steady state cycle analysis (cycle balance) of the LRES should be carried out for components from the same level of shown hierarchy. Generally in descending design systems, the initial data for all components of LRES are formed by the user at the initial design stage. This approach requires large computational resources for the solution convergence of the considered problem. According to this approach, the ports of two adjacent components of LRES are consistently if they have the same state variables and their numerical values coincide with the specified precision. For given homogeneous parameters quantitative estimates of inconsistent ports is a residual (or discrepancy)- $\Delta X = X_{out} - X_{in}$. For eliminating the inconsistency of components' ports a system of equations is formed. Thus, if the output variables' vector of are considered then we can write

$$\mathbf{X} = \begin{bmatrix} X_1 \\ X_2 \\ . \\ . \\ X_i \end{bmatrix} = \begin{bmatrix} output\ parameter\_1 \\ output\ parameter\_2 \\ . \\ . \\ output\ parameter\_i \end{bmatrix}$$

Then the nonlinear system of equations can be defined as follows (Fig.3):

$$\mathbf{F(X)} = \begin{bmatrix} f_1 \\ f_2 \\ . \\ . \\ f_i \end{bmatrix} = \begin{bmatrix} equation\_1 \\ equation\_2 \\ . \\ . \\ equation\_i \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ . \\ . \\ 0 \end{bmatrix}$$

For example, consistently of parameters (power balance) values for turbine, oxidizer and fuel pumps' can be described by the equation

$$\eta_t N_T = N_{P.ox}(p_{2.ox}, \dot{m}_{ox.CC}, \dot{m}_{ox.GG}) + N_{P.f}(p_{2.f}, \dot{m}_{f.CC}, \dot{m}_{f.GG})$$

$$F_4^{'} = p_{2.f} - p_c - \Delta p_f = 0$$

$$F_8^{'} = p_{2.ox} - p_c - \Delta p_{ox} = 0$$

$$F_4^{''} = \dot{m}_f - \dot{m}_{f.CC} - \dot{m}_{f.GG} = 0$$

$$F_8^{''} = \dot{m}_{ox} - \dot{m}_{ox.CC} - \dot{m}_{ox.GG} = 0$$

$$F_9 = \dot{m}_{ox.T} - \dot{m}_{f.GG} = 0$$

$$F_{13} = \eta_t N_T - N_{P.ox}(p_{2.ox}, \dot{m}_{ox.CC}, \dot{m}_{ox.GG}) + N_{P.f}(p_{2.f}, \dot{m}_{f.CC}, \dot{m}_{f.GG} = 0 \text{, etc.}$$

Approximation of all residuals to zero (with given accuracy) is the central mathematical operation of such LRES design system. The number of residuals formed for the considered engine scheme determines the dimension of the system of algebraic equations that needs to be solved. To solve such a system of equations, it is necessary to assign a group of variables. A number of variables should be equal to the number of residuals. The process of reducing the residuals to zero is carried out in an iterative manner. As a result, the balance of the LRES scheme is provided.

Moreover, if the residual and the variable are a same type (for example, $\Delta X_1 = \Delta p,\ X_1 = p$) then the variable p is corrected by the residual value Δp. In case of existence of inhomogeneous pairs of residuals ($\Delta X_1 = \Delta p,\ \Delta X_2 = \Delta \dot{m}$), the correction of the changed variable $\dot{m}$ is implemented using a solver - the Newton-Raphson method. It should be noted that the use of this approach requires a large amount of initial data, large computing resources and does not guarantee a fast convergence of the solution [Vazquez et al., 2010; Lebedinsky et al., 2009; Sydorenko and Nikishchenko, 2015]. Note that, due to the lack of comprehensive initial information, there are deviations from the potentially possible optimal technical results.

Therefore, the optimality of the results of the block-hierarchical design (hybrid design) of LRES should be considered from two points of view:

1) technical parameters of LRES (thrust, consumption of fuel components, weight, etc.),

2) economic indicators (material and time costs for design, etc.).

In another case at the descending design of LRES uncertain conditions often arise. Since the main parameters of the LRES components or elements have not yet been determined, i.e. LRES components have not yet been designed. In this case, unrealizable technical requirements for the components of the lower level in hierarchy can be formulated.

Taking into account the results of the analysis of the disadvantages and advantages of the considered approaches, in this paper a hybrid structure of LRES design system have been offered, which is considered in the next paragraph.

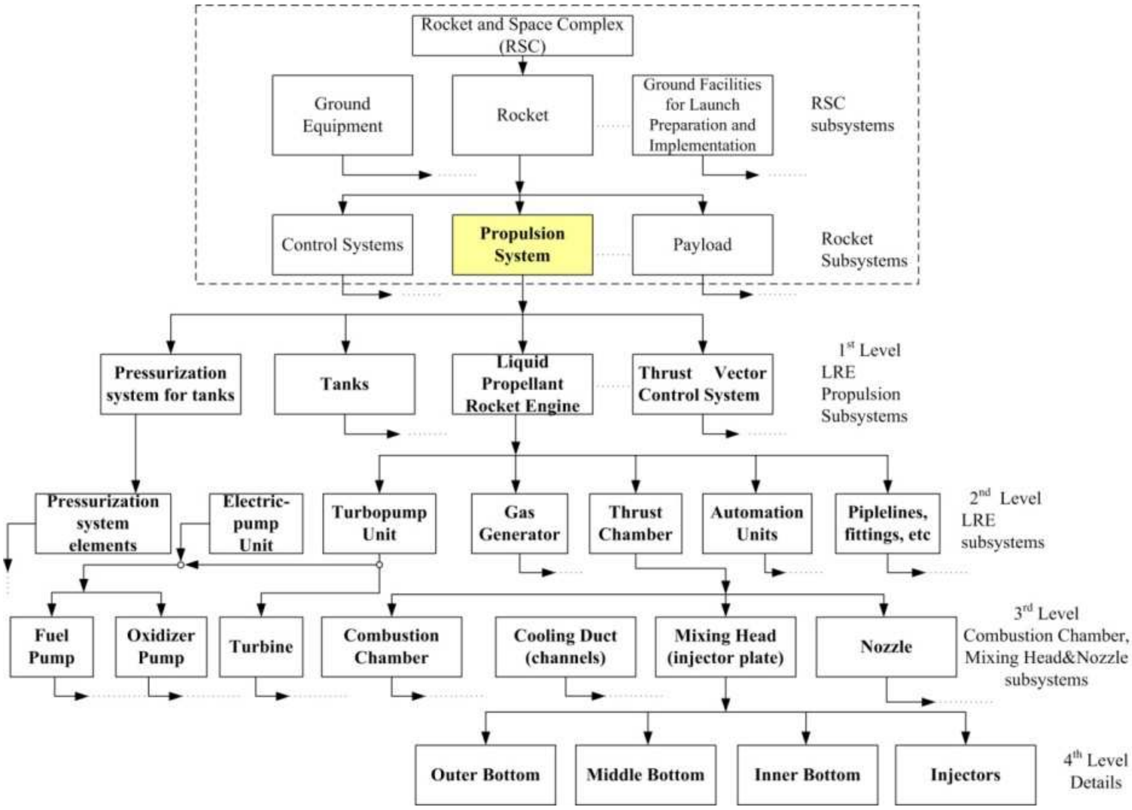

Figure 2: Hierarchical Structure of LRES as Part of Rocket

HYBRID CONCEPT FOR LRES DESIGN SYSTEM

For the effective use of the computational procedures, the structure of LRES design system is considered as a hybrid concept. According to this concept, LRES is designed in a combined structure (top-down and bottom-up) using components' local deterministic models.

Thus, a part of the initial data of LRES components is generated at the top-down (descending) design stage. Missing parameters and new constraints for LPES components are formed by the user-engineer (experimental data, design experience, customer requirements) at the bottom-up (ascending) design stage. The LRES components' ports inconsistency are refined or eliminated using the Newton-Raphson solver at the ascending design stage.

For implementing this design principle, LRES is considered as a system consisting of the following sequential modules and submodules (for pump-fed LRES scheme):

Module “Thrust Chamber" - combustion chamber, nozzle,

Module “Cooling Duct”,

Module "Turbopump Unit" - oxidizer pump, fuel pump, turbine, manifold

Module "Gas Generator" – gas generator, manifold

Module "Tanks" - oxidizer tank, fuel tank, pipes

The structure of this design system is shown in Fig.3. In first stage LRES is designed (descending design) in the sequence: Thrust Chamber-Cooling Duct-Turbopump Unit-Gas Generator-Tanks (calculation all engine cycle components in a sequential loop). Each subsequent module is calculated and designed only after obtaining satisfactory design results of the previous module. Design results of the previous modules are the initial data and (or) boundary conditions for design of subsequent modules. The second stage is an ascending design with the addition of new data and constraints, where for quickly achieving a global goal the initial data can changed. At this design stage are solved set of 13 systems of equations. Inconsistencies in the results of computing submodules are eliminated by the Newton-Raphson solver.

It should be noted that analytical models for estimation of parameters (variables) of LRES' main units a are given in many manuals [Kozlov et al., 1988; Humble et al., 1995; Vasiliev et al., 1983].Thus, the main elements of the projected LRES, their initial data, port variables and calculation results are shown below (Fig. 3):

Thrust Chamber (TC)

Input port: $p_c, T_c,$- total pressure and temperature in the combustion chamber (CC), K_m- mixture ratio at the CC inlet.

Initial data (results of the thermogasdynamic calculation of the thrust chamber): p_h-ambient pressure, $\dot{m}_{ox.CC}, \dot{m}_{f.CC}$-propellant components (oxidizer, fuel) mass flow rate at CC inlet, μ_{nozzle}, φ_{nozzle}-nozzle flow rate coefficient, nozzle losses coefficient, A_{th}, A_e-nozzle throat and exit areas, A_{CC}, L_{CC}-combustion chamber cross section area and length, $\beta_{1.noz}$, θ_n, θ_e-entry angle into the subsonic part of the nozzle, supersonic nozzle entry angle, nozzle exit angle, $K_{m.wall}$-fuel components mixture rate in the boundary layer (about nozzle inner wall).

Estimation: P_0- thrust at sea level, $I_{sp.v}$-specific impulse at vacuum, R_i, L_i-distribution radius and length of the chamber cross section along the axis, L_i, L_{th}, R_i, R_{th}-length and radius of the considered point and nozzle throat of the chamber profile, $\bar{x} \propto f(L_i / L_{th}), \bar{y} \propto f(R_i / R_{th})$-relative coordinates of the TC contour profile, $\bar{x} \propto f(L_i / L_{th})$-relative coordinates for subsonic and supersonic nozzle parts and for cylindrical CC.

Output port: p_c-pressure in the CC, P_0- thrust at sea level, P_v- thrust at vacuum, β - consumable complex of the thrust chamber, $I_{sp.0}$-specific impulse at sea level, $I_{sp.v}$ - specific impulse at vacuum, p_e-nozzle exit pressure, ε -gas expansion degree in the LRE chamber D_e-nozzle exit diameter, K_m-actual fuel components mixture ratio in the CC, M_e-Mach number of the gas flow at the nozzle exit, $\overline{A} = A_e / A_{th}$-nozzle area ratio, Δp_{CC}-pressure drop along CC, $H_{fuel.0}$ -initial fuel enthalpy.

Cooling Duct (CD)

Input port: $p, T, \dot{m}_c, \rho, C_p$-pressure, temperature, mass flow rate, density and spesific heat of the coolant at CD inlet, A_Σ-total cooling wall surface area.

Initial data: n-coolant component, M-wall material, $q_{\Sigma.i}$-specific heat flux entering to the inner wall along chamber axis, A_{Σ}-total cooling wall surface area, A_w-effective cooling wall surface area, $\bar{x} \propto f(L_i / L_{th}), \bar{y} \propto f(R_i / R_{th})$- relative coordinates of the thrust chamber for the coolant duct, a-cooling groove width, b, h-width and height of the cooling film ribs, δ-thickness of the chamber internal wall $p_2 - p_1 = \Delta p$, $T_2 - T_1 = \Delta T$-expected changes of the coolant in CD.

Estimation: Q_{Σ}-removing heat with coolant, $\dot{m}_c$-coolant mass flow rate, p_2, T_2-coolant pressure and temperature at CD exit.

Output port: $p, T, \dot{m}_c$-pressure, temperature and mass flow rate.

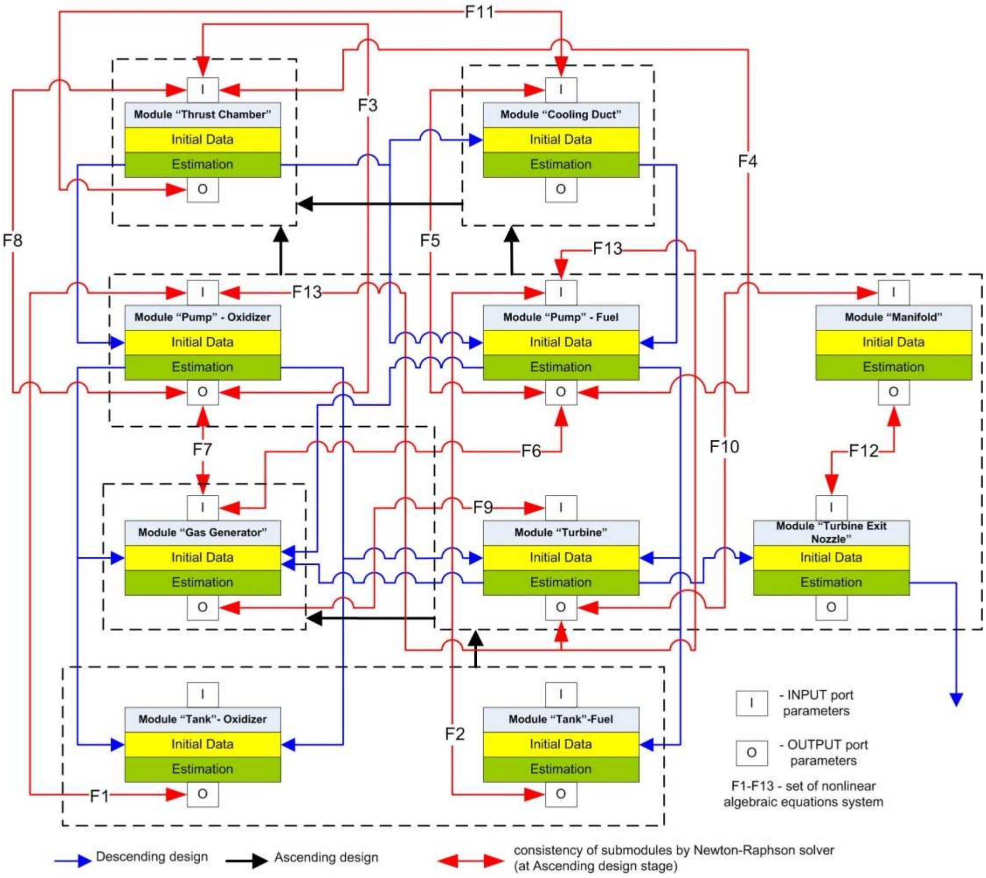

Figure 3: Hybrid Concept of LRES Design System (set of 13 Systems of Equations)

Turbine (T)

Input port: p_0, T_0- gas total pressure and temperature at inlet, $\dot{m}_T$-gas mass flow rate at inlet

Initial data: $\dot{m}_T$-gas mass flow rate at inlet, p_0, T_0- gas total pressure and temperature at inlet, N_T-turbine power or η_T-turbine efficiency, n_T-rotating speed of the turbine shaft, p_2-gas outlet pressure or Δp-pressure discharge, R-inlet gas constant, C_p-heat capacity, γ-specific heat ratio of the inlet gas.

Estimation: $\dot{m}_T$ or Q_T-gas mass or volume flow rate through turbine, π_T-pressure ratio, L_T-effective work of the turbine, M_T-torque, N_T-effective power of the turbine, η_T-turbine efficiency, geometrical and kinematical parameters of the turbine.

Output port: p_2, T_2- gas pressure and temperature at outlet, $\dot{m}$-gas flow rate, N_T-power of the turbine,

Pump (P)

Input port: p_1, T_1, ρ_1-total pressure temperature and density of component at inlet, $\dot{m}$ -fuel component mass flow rate, K_m-fuel components mixture ratio, C_p-heat capacity of component.

Initial data: $\dot{m}_{P.o}$, $\dot{m}_{P.f}$ -fuel component mass flow rate, $p_{1.\min}$ - minimum total pressure at inlet into pump, $T_{1.\max}$-maximum temperature of component at inlet, p_2-total pressure of feed, $\rho_{f.c}$ -density of component, p_s-pressure of vapors, ν -kinematic viscosity of component, n_P-rotating speed, n_s-power-speed coefficient.

Estimation: η_P-pump efficiency, H_t-theoretical pressure, N_P-net power of the pump, n_P-rotating speed, geometrical and kinematical parameters of the pump.

Output port: $\dot{m}_{P.o}$-fuel component mass flow rate, p_2-total pressure of feed, N_P-power of the pump, K_m-fuel components mixture ratio.

Gas Generator (GG)

Input port: $p, T, \dot{m}, \rho, R, C_p$-pressure, temperature, mass flow rate, density, gas constant, heat capacity of the generator gas, K_m- fuel components mixture ratio in the GG.

Initial data: Fuel components, $\dot{m}_{ox.GG}$, $\dot{m}_{f.GG}$ -propellant components (oxidizer, fuel) mass flow rate at GG inlet, ρ_O, ρ_F -components density, T_{GG}- gas temperature, A_{GG}-gas generator cross section area, τ_{GG}-engine working time.

Estimation: R_{GG}- gas constant, $n_{is.}$-isentropic index, p_{GG}-outlet gas pressure, $\dot{m}_{GG}$-gas mass flow rate, β_{GG}-consumable complex of GG, $\bar{g}_{GG}$ -flow rate tension of GG.

Output port: $p, T, \dot{m}, \rho, R, C_p$-pressure, temperature, mass flow rate, density, gas constant, heat capacity of the generator gas, $K_{m.GG}$- fuel components mixture ratio in the GG.

Manifold (M)

Input port: $p, T, \dot{m}, R, C_p, \gamma$-pressure, temperature, mass flow rate, gas constant, heat capacity, specific heat ratio of gas, K_m- fuel components mixture ratio.

Initial data: $\dot{m}, T, R, C_p, \gamma$- mass flow rate, temperature, gas constant, heat capacity, specific heat ratio of gas at inlet.

Estimation: A_M -manifold cross section area, $\pi_M = p_2 / p_1$-pressure ratio in manifold, Δp-pressure drop in manifold.

Output port: $p, T, \dot{m}, R, C_p, \gamma$-pressure, temperature, mass flow rate, gas constant, heat capacity, specific heat ratio of the gas

Turbine Exhaust Nozzle (TEN)

Input port: $\dot{m}$- gas mass flow rate

Initial data: p_h-ambient pressure, P_v- thrust at vacuum, φ_c, φ_n-chamber and nozzle losses coefficient, p_e-nozzle exit pressure or $\bar{A}$-nozzle area ratio.

Estimation: P_0- thrust at sea level, P_v- thrust at vacuum, $I_{sp.0}$-specific impulse at sea level, $I_{sp.v}$-specific impulse at vacuum, β -consumable complex, ε -gas expansion degree of the

TEN, $\overline{A}$-nozzle area ratio, A_{th}, A_e-throat and exit areas, p_e, M_e-pressure and Mach number of nozzle exit flow.
Output port: $\Delta p = p_e - p_h$-exit gas and ambient pressure difference.

Tank (TN)
Input port: propellant component, $p, T, \dot{m}, \rho, C_p$-pressure, temperature, mass flow rate, density, heat capacity of component at inlet to engine, K_m - fuel components mixture ratio in the CC.
Initial data: propellant component, $p, T, \dot{m}$-pressure, temperature and mass flow rate of component
Estimation: p_s, H-pressure and enthalpy of component.
Output port: $p, T, \dot{m}, \rho, C_p$-pressure, temperature, mass flow rate, density, heat capacity of component at inlet to engine, K_m - fuel components mixture ratio.

Thus, at the first stage, design of LRES is carried out at the module level according to the Thrust Chamber-Cooling Duct-Turbopump Unit-Gas Generator-Tanks sequence. The computational results of first design stage of the LRES are input data for second design stage. In the second design stage are added new parameters and their values (constraints) to the estimated parameters by engineer-researcher. As a result, a discrepancy appears between the inputs and outputs of different LRES's units. Therefore, to eliminate these discrepancies, it is necessary to use the Newton-Raphson solver. Such organization of LRES design process allows correctly distributing tasks and efficiently using computational resources.

CONCLUSION

This design scheme for LRES allows an effective combination of theoretical and experimental data.

Sequential formation of the initial (theoretical) and input (experimental data, design experience, customer requirements) data at descending and ascending stages of LRES design allows us to reduce the number of nonlinear algebraic equations describing the variables' residuals between components. As a result, calculation cycles are reduced and is achieved fast convergence using the Newton-Raphson solver.

The implementation of this design scheme makes it possible to determine the values of all ports' necessary variables of all LRES components (mass flow rate in all pipelines or manifolds, required pump pressure, pump and turbine power, pressure and temperature of liquid components and combustion products, specific impulse, thrust, etc.).

Note that, the success of designing an optimal LRES strongly depends on the accuracy of calculating the combustion and flow processes in the thrust chamber.

Having carried out a series of calculations at different pressures in the engine chamber, it is possible to construct the variation of the specific impulse with different design parameters and LRES scheme.

Currently is being developed WEB-based software based on the proposed approach for LRES design.

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