DEVELOPMENT OF HIGHLY COMPETITIVE LIQUID ROCKET ENGINES IN TIME OF SPACE GOLD RUSH

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ABSTRACT

The competition in the launch industry is getting more tight and dynamic. In these circumstances, the launch vehicle development duration becomes extremely important as well as minimizing launch cost. The engine cost is the most significant fraction of total vehicle cost. One of the potential ways to reduce development duration and cost is through using a system design approach applied to liquid rocket engine optimization taking into account the mass and dimensional constraints.

The authors of this paper, utilizing a system engineering approach, started the development of the design system focused on the preliminary design of the entire liquid rocket engine and its components. The preliminary estimation of the liquid rocket engine cycle parameters, preliminary design of the turbopump and a thrust nozzle were considered in the authors' previous paper. This paper describes the task of optimum engine layout, considering a number of criteria. Crucial aspects of parallel and sequential engine layouts are discussed. The orientation of the turbopump relative to the thrust nozzle gyroscopic effects were taken into account. Optimal engine layout search peculiarities for first, second and upper stages are described.

All the aspects of optimal liquid rocket engine layout selection were implemented in an integrated system of physic based models which allow searching for the best possible configuration within the defined constraints. The results of the application of the system and benefits from its utilization are presented.

INTRODUCTION

Over the past few years, digital engineering got widespread in different industrial spheres[1]. Digital engineering is the approach that focuses on the utilization of different integrated models covering the stages of object design, analysis, test, and optimization.

For the rocket engine, the development level is one of the most significant contributors to the time and cost consequently. Application of digital engineering for the rocket engine development allows significantly reduce the development time replacing laborious processes by automatic one.

SoftinWay Inc. continues its work on the development of the system engineering approach for the preliminary design of entire rocket engine including turbopump starting from the cycle estimation with the preliminary estimation of rocket mass and a number of stages based on required payload and orbit data and finishing the preliminary engine layout.

One of the criteria that impacts the turbopump configuration selection is the turbopump mass. The specific impulse renders the most significant impact on the selection of the optimum turbopump configuration. The influence of this specific impulse is about an order higher than the influence of difference in turbopump mass, so the mass of pipes cannot actually influence the selection. However, in a previous paper[4] couple of considered configurations of the turbopump were very close by mass and specific impulse, i.e. the difference in mass of turbopump plus mass of propellants required to drive turbopump between the turbopump configurations was very small and comparable to the mass of pipes. Hence, accounting for the additional mass of connecting pipes on the engine layout level can change the selection of the optimum turbopump configuration.

The rocket engine layout is the joint arrangement of its component relative to each other that satisfy the number of often contradictory requirements[2,3]:

- Compactness and minimal weight of engine
- Minimal hydraulic and heat losses in pipelines
- Static and dynamical strength of separated engine components and engine in general
- Convenience and ease of installation and operation of a rocket engine

The current study is devoted to the development of an integrated approach which allows automatically performing a joint turbopump-engine layout preliminary geometry generation and selection of the best engine configuration taking into account the criteria mentioned above.

ROCKET ENGINE MAIN COMPONENTS AND THEIR SIZES

Preliminary assembling of the rocket engine in general case contains turbopump, thrust nozzle, and combustion chamber, pipelines and gas generator.

It is assumed that the current study is the next step after the preliminary design of turbopump and that the turbopump dimensions and mass are known and were determined after the execution of turbpopump configuration selection algorithm[4].

Preliminary design of turbopump is based on an iterative approach that was implemented in the integrated system and includes the following activities:

- Oxidizer pump preliminary design
- Fuel pump preliminary design
- Turbine preliminary design
- Turbopump preliminary layout development
- Rotor mass/inertia parameters preliminary determination
- Estimation of axial and radial forces on bearings, bearings simulation and rotor dynamics analysis
- Secondary flows (leakages) system analysis and determination of the required amount of propellant for each bearing branch
- Preliminary stress analysis of turbomachinery components
- Preliminary selection of the configuration

The result of the preliminarily designed turbopump (Exhibit 1) and a thrust nozzle (Exhibit 2) are presented below. It should be noted that 7 different turbopump configurations were considered (Exhibit 3).

The following rocket engine components are taken into account: turbopump, thrust nozzle, and combustion chamber connecting pipes and gas generator. In addition, the simplified models of the controller of fuel components and trust controller are added.

The formulations and assumptions used for the determination of pipes and gas-generator dimensions are presented below.

Pipe diameters. The preliminary inner diameter of pipes can be determined based on propellants mass flow rate utilizing continuity equation

$$A = MFR/(W*\rho)$$

where

A – pipe circumference area, m^2;

ρ – propellant density, kg/m^3;

MFR – propellant mass flow rate, kg/s;

W – propellant flow velocity in the pipe. Based on the general recommendation the propellant flow velocity is 10 – 25m/s.

The propellants MFRs and their density are known from the cycle estimation level.

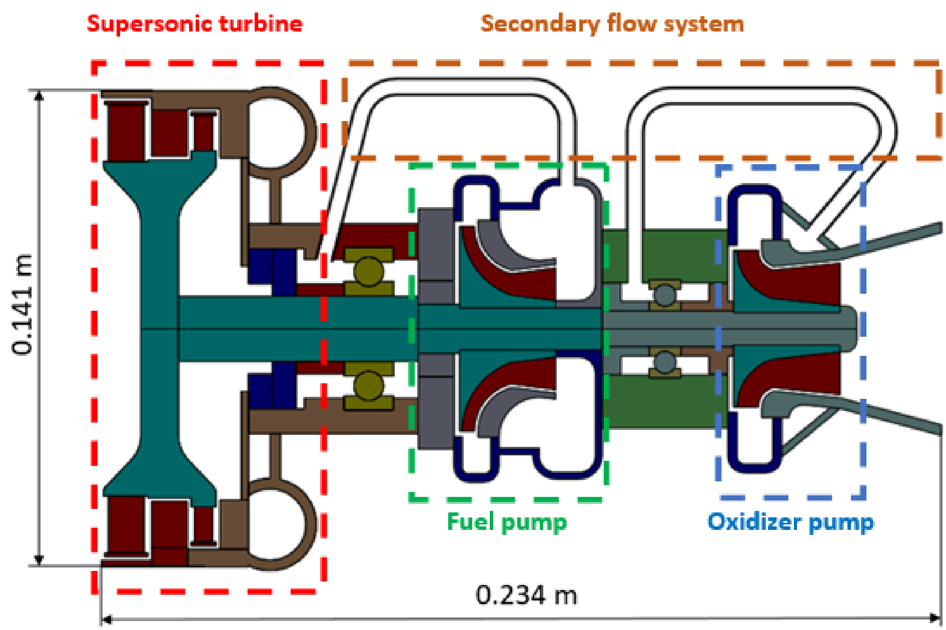


Exhibit 1: Sketch of the turbopump

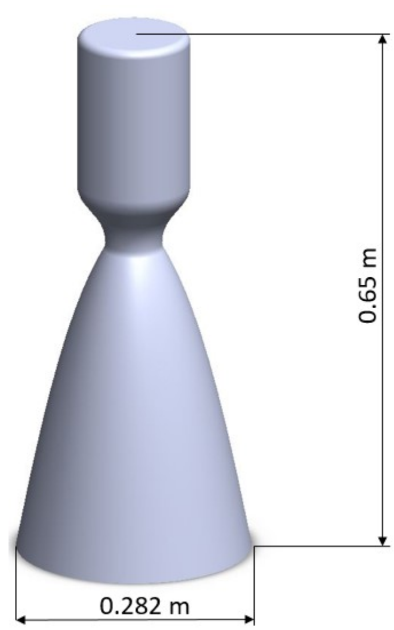


Exhibit 2: Sketch of the thrust nozzle

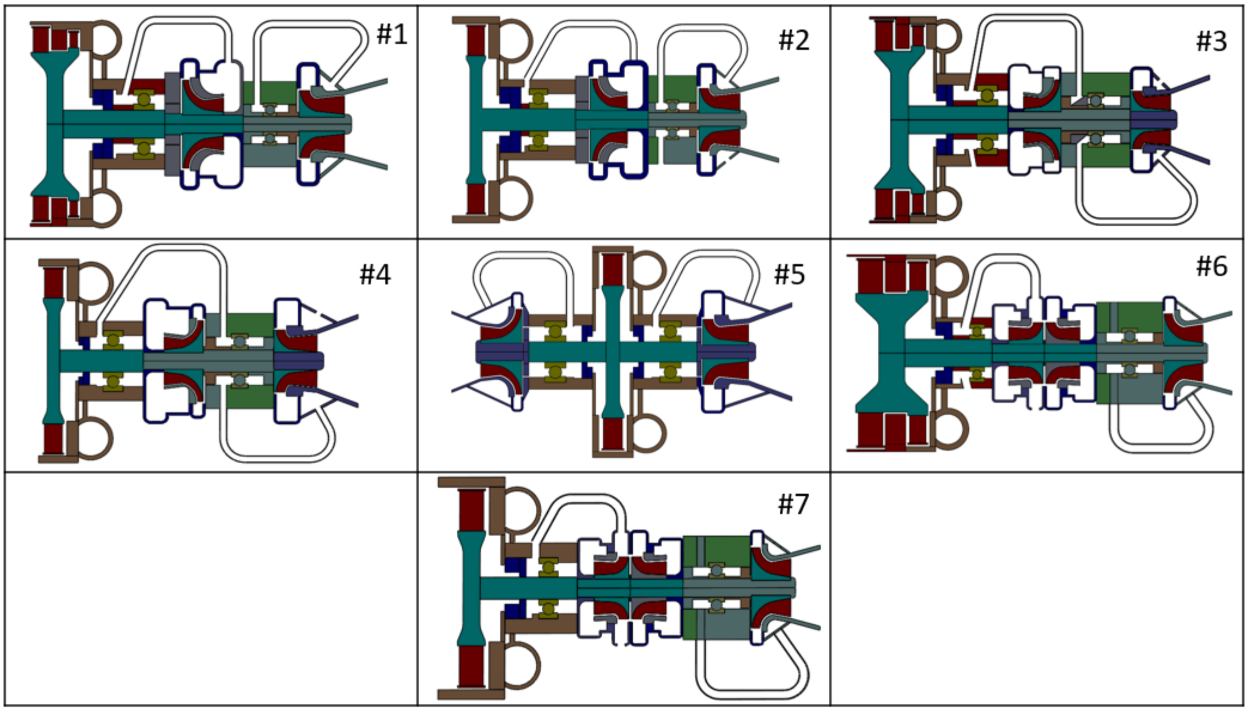


Exhibit 3: Considered configurations of the turbopump

Gas generator dimensions. The volume and sizes of the liquid gas generator can be determined from the condition of stay time of fuel and combustion products in the gas generator[5].

$$\tau = V^* P/(MFR^*R^*T)$$

where

τ –a time of stay of combustion products in the gas generator, s;

MFR – mass flow rate of combustion products, kg/s;

P, T, R – pressure (Pa), temperature (K) and gas constant (J/kg*K) of combustion products correspondently. Presented above, the parameters were determined at cycle estimation level based on optimal oxidizer excess ratio to provide maximal specific impulse value. CEA tool[6] is utilized for this goal.

For the different fuels, τ is determined experimentally and lies in the range 0.002 – 0.015 s.

TASK FORMULATION

The reduction of the engine development time at the engine layout design stage can be achieved by application of the algorithm that allows varying the interposition of engine components with simultaneous estimation of required parameters taking into account following constraints: maximal compactness, minimal mass, and gyroscopic momentum.

During preliminary rocket engine layout creation it is necessary to determine the location of the components that have maximal mass and their influence on engine working behavior.

Generally interposition of engine components are determined by:

- engine purposes, number of chambers
- required dimensions of engine section
- constructive, manufacturing and economic requirements

Taking aforementioned into account, the variety of engine layouts is pretty wide. The goal of the previous authors' paper was the development of turbopump for a single chamber expander open cycle engine for the first stage of a launcher. Therefore, in order to be able to use the design system developed in the previous paper the single chamber engine with one single rotor turbopump is chosen in this paper as well. In this paper, the design system was extended to take into account the engine layout and related criteria. It important to notice that the design system is not limited to the considered configurations and layouts or cycle types, it can be easily extended and enhanced.

For the single chamber engines, there are two types of engine components interposition: parallel and consequent. With parallel location, turbopump is located at the nozzle side with the parallel or perpendicular location of nozzle and turbopump axes. Consequent location means the location of turbopump over the combustion chamber.

Preliminary rocket layout criteria include:

- **Engine compactness.**

For single chamber engines, the turbopump is located as close as possible to the combustion chamber. It allows decreasing of hydraulic losses in the pipes. Improvement of compactness criterion leads to a reduction of rocket cross section and consequently to the reduction of aerodynamic losses for the launcher.

The compactness of rocket engine layout can be estimated by compactness coefficient that represents the ratio of the summary volume of all elements to the volume of cylinder circumscribed around the engine.

$$C = V_{\Sigma} / V_{cyl}$$

where

C – compactness coefficient;

V_{Σ} – the sum of all engine elements volumes;

V_{cyl} – the volume of cylinder circumscribed around the engine.

- **Gyroscopic momentum.**

With the curvilinear trajectory of the rocket and certain circumferential velocity, the gyroscopic momentum takes place[7]. The reactive momentum of rotor rotation influences the control of trajectory. Therefore this parameter should be accounted for during the rocket engine layout determination.

The gyroscopic moment is given by

$$M = J*\omega*\Omega*SIN\theta, \text{ when } \omega >> \Omega$$

where

J – inertia momentum of turbopump shaft mass;

ω – circumferential velocity of turbopump shaft;

Ω = V/R – rocket circumferential velocity (V-rocket velocity at a current point, R – radius of trajectory curvature);

Θ – angle between ω and Ω.

In the case of Θ is equal to 90 degrees the value of gyroscopic momentum has a maximal magnitude. In turn, Θ =0° leads to M=0. For the small rockets that do not have active stabilization controls, the value of gyroscopic momentum has a significant influence obstructing the rocket turn. For the large rockets, the influence of gyroscopic momentum is not significant.

- **Engine mass.**

As the LRE main components (turbopump, nozzle, gas generator, etc.) under layout creation have a fixed mass, the LRE mass is proportional to the pipes lengths. The main mass criterion was the sum of the turbopump mass, mass of fuel required to drive turbopump and mass of the pipes. It was assumed that the thrust nozzle mass is the same for all layouts and configuration and thus was not included in the mass criterion determination.

- **Heat fluxes from the combustion chamber and nozzle exit.**

The accounting for the heat fluxes from the combustion chamber and reactive stream at nozzle exit is important during LRE layout creation. The heat shields, insulating covers are utilized to protect the engine components[7].

The estimated magnitudes of the heat fluxes help to determine the interposition of turbopump relative to nozzle and/or make the conclusion regarding the selection of insulating materials and their thickness. The main aspect of heat influence accounting is the calculation of the temperature of inner turbopump and pipes walls temperature. Increasing of cryogenic elements temperature to the temperature of saturation or higher leads to fluid evaporation and incorrect work of pump.

Preliminary heat flux estimation from steam at nozzle exit can be estimated by heat transfer theory utilizing the specified thermal conductivity coefficient that accounts for the influence of convection and radiant fractions.

In the case of regenerative cooling of the nozzle and combustion chamber for correct calculation of heat flux, it is necessary to account the changing of coolant temperature moving through trust nozzle.

Calculated heat fluxes can be used to estimate the thermal stresses of nozzle and combustion chamber and accounting of their influence of turbopump and pipes with LOX. In the case, if heat fluxes do not influence significantly the condition of LOX at turbopump it is located as close as possible to the combustion chamber.

Estimation of the heating of cooling fluid through the nozzle was done utilizing AxSTREAM NET™ tool[8]. The example of nozzle cooling simulation is presented in Exhibit 4.

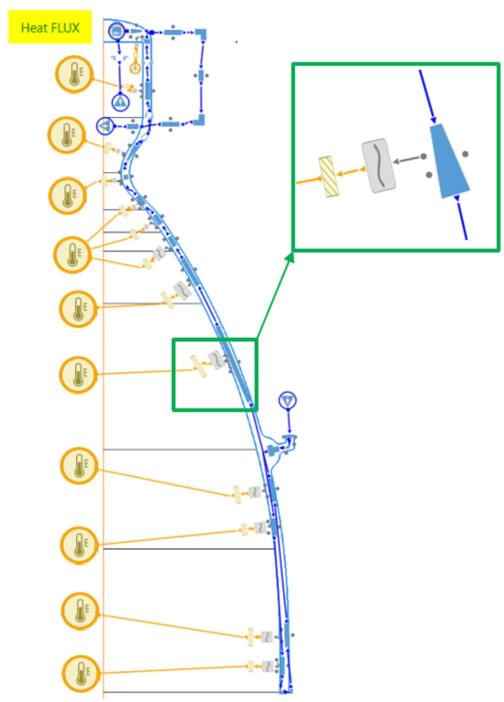


Exhibit 4: Nozzle cooling simulation in AxSTREAM NET™

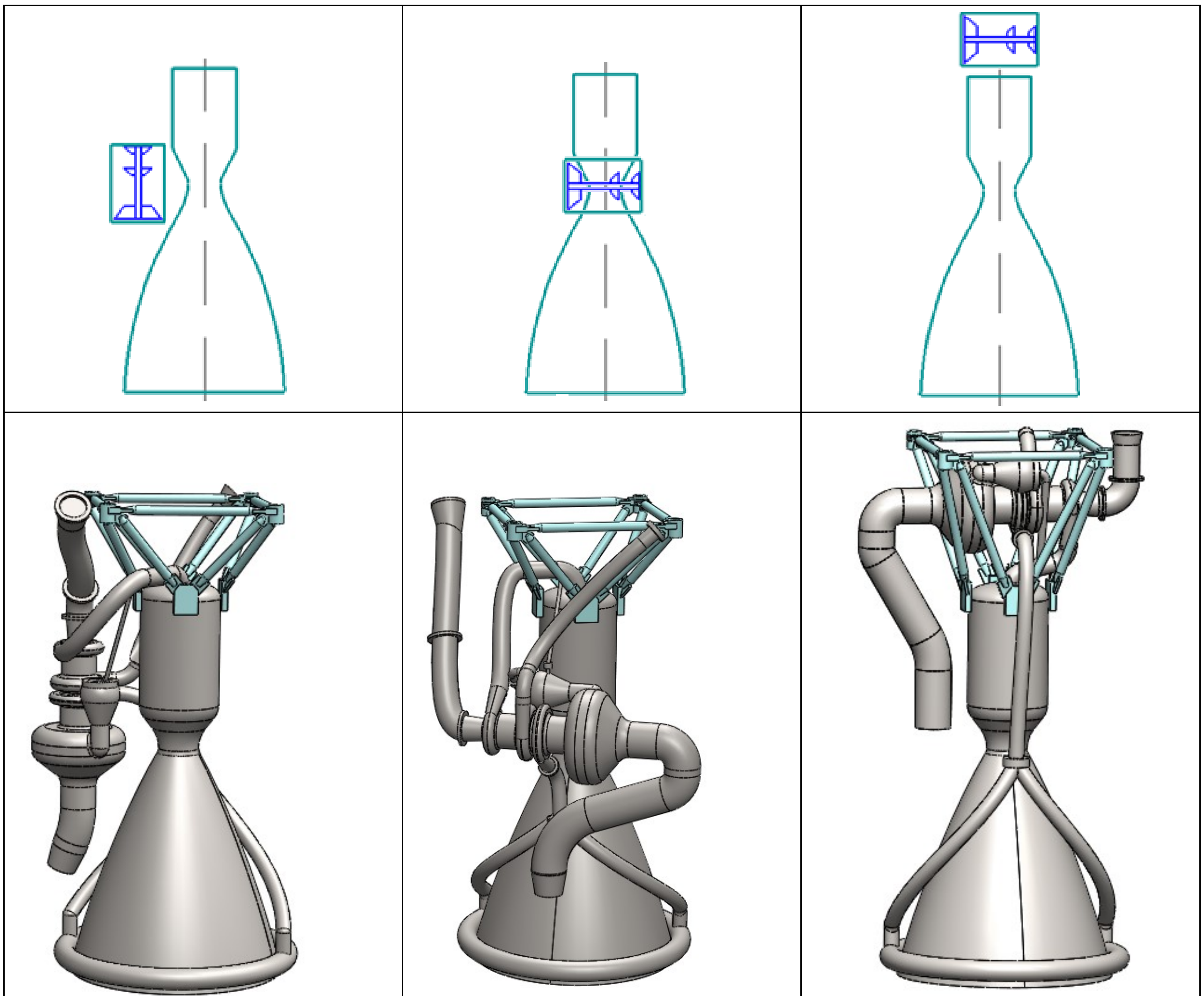
Taking into account that the current study is based on conceptual design of liquid rocket engine, preliminary assessment of heat fluxes and strength calculation (for example, the influence of pressure pulsation in the combustion chamber on turbopump) were performed only. Detailed assessment of these factors will be performed during consequent studies to extend the capability of the integrated system being developed.

Engine layouts.

In the scope of this paper, three layouts of the engine were considered. The examples of the layouts are presented in Exhibit 5. At first configuration (Exhibit 5a) the turbopump is located at the side of thrust nozzle. The axis of rotation of turbopump rotor is parallel to the nozzle axis. Perpendicular orientation of axis of rotation of the turbopump to the nozzle axis is presented on Exhibit 5b. The third layout (Exhibit 5c) represents the turbopump location over the thrust nozzle. It should be noted that these layouts are just the specific cases considered in this paper. The other orientations can be easily added, including non-perpendicular or non-parallel ones.

Within each layout the interposition of the turbopump was a variable, which was determined during the optimization algorithm.

It should be noted that the location of tanks and their sizing were not included in the design process in this paper.



a)	b)	c)

Exhibit 5: Considered Examples of Rocket Engine Layouts

Process flowchart.

The algorithm of LRE automatic layout creation was implemented in the integrated environment and presented below (Exhibit 4).

According to the algorithm, the LRE layout development starts from the transfer of the turbopump geometry and nozzle performed by the design system described in the previous paper[4]. The turbopump and nozzle data go to the nozzle cooling calculation procedure (red rectangle in Exhibit 6), where the heat fluxes are being estimated. It should be noted that the heat fluxes from the nozzle exit side and combustion chamber side were calculated taking into account the nozzle geometry; fuel data and temperature distribution inside the nozzle; and the combustion chamber. After that for each engine layout the procedure of the turbopump optimum interposition determination is performed (green rectangle in Exhibit 6). All seven configurations of the turbopump (Exhibit 3) are taken into account and for each of them the optimum interposition was determined within the given layout. The CAD models similar to those shown in Exhibit 6 are automatically generated during the determination of optimum interposition for all the layouts with each considered configuration of the turbopump. Pipes layout generation and their mass estimation were the part of the algorithm, i.e. pipes mass was included in the mass criterion for each considered case. Then the preliminary cooling channels number estimation, engine mass criterion estimation, compactness criterion, gyroscopic momentum calculation and eventually the best layout determination is performed. After execution of the algorithm, all the data are stored in an Excel file.

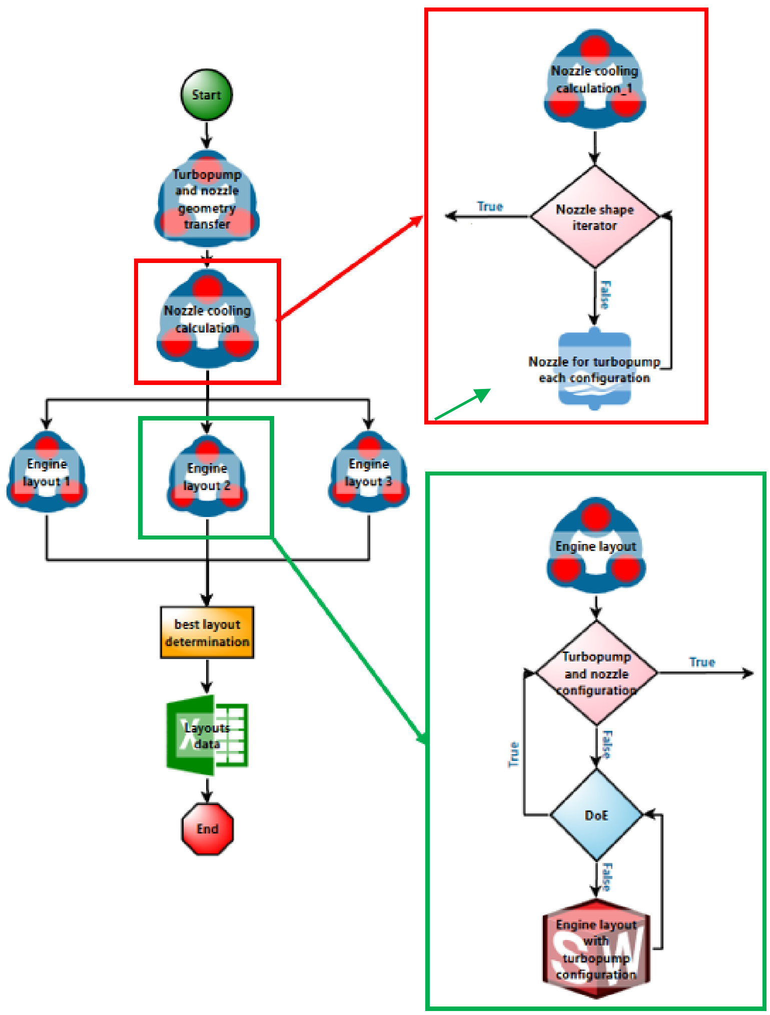


Exhibit 6: Execution process flow chart

Optimization algorithm is based on Design of Experiment theory (DoE). The criteria for the best layout and configuration were the minimum mass and maximum compactness. Gyroscopic momentum was an additional criterion taken into account.

ROCKET ENGINE LAYOUT SELECTION RESULTS

Utilizing the developed automated approach, the preliminary rocket engine layout creation was performed. The results of the study are presented in table (Exhibit 7).

Turbopump layout	Parameter	1	2	3	4	5	6	7
Engine Layout 1	Pipes mass, kg	0.857	1.071	0.868	1.098	1.250	1.176	1.201
	Turbopump mass, kg	11.97	11.16	12.25	11.81	11.93	12.4	12.15
	Compactness	0.194	0.158	0.192	0.157	0.161	0.191	0.158
	Gyroscopic momentum, N*m	$2.2*10^6\Omega$	$2.2*10^6\Omega$	$2.2*10^6\Omega$	$2.2*10^6\Omega$	$2.2*10^6\Omega$	$3.1*10^6\Omega$	$3.1*10^6\Omega$
	Total mass, kg	12.82	12.23	13.11	12.90	13.18	13.57	13.35
	Engine specific impulse, s	310.69	309.19	310.54	308.98	308.98	310.73	309.23
	Propellants mass to drive TPU, kg	59.98	75.26	61.59	77.39	77.39	59.66	74.83
	Mass criterion, kg	72.80	87.49	74.70	90.29	90.57	73.23	88.18
Engine Layout 2	Pipes mass, kg	0.94	1.01	0.947	0.99	0.98	1.34	1.39
	Turbopump mass, kg	11.97	11.16	12.25	11.81	11.93	12.4	12.15
	Compactness	0.182	0.149	0.179	0.147	0.152	0.181	0.173
	Gyroscopic momentum, N*m	0	0	0	0	0	0	0
	Total mass, kg	12.91	12.17	13.19	12.80	12.91	13.74	13.54
	Engine specific impulse, s	310.69	309.19	310.54	308.98	308.98	310.73	309.23
	Propellants mass to drive TPU, kg	59.98	75.26	61.59	77.39	77.39	59.66	74.83
	Mass criterion, kg	72.89	87.43	74.78	90.19	90.3	73.40	88.37
Engine Layout 3	Pipes mass, kg	0.69	0.77	0.72	0.806	0.88	1.095	1.171
	Turbopump mass, kg	11.97	11.16	12.25	11.81	11.93	12.4	12.15
	Compactness	0.193	0.174	0.193	0.173	0.177	0.193	0.184
	Gyroscopic momentum, N*m	0	0	0	0	0	0	0
	Total mass, kg	12.63	11.93	12.97	12.61	12.81	13.49	13.32
	Engine specific impulse, s	310.69	309.19	310.54	308.98	308.98	310.73	309.23
	Propellants mass to drive TPU, kg	59.98	75.26	61.59	77.39	77.39	59.66	74.83
	Mass criterion, kg	72.61	87.19	74.56	90	90.2	73.15	88.15

Exhibit 7: LRE parameters with different layout configurations

Engine layout #1 provides lower values of pipes mass with the maximal compactness value. However, maximal gyroscopic momentum takes place for this layout, due to 90 deg angle between rotational axes of rocket and turbopump rotor, which can significantly influence the trajectory of the rocket.

It can be seen from the results that engine layout #2 provides maximal pipes mass for the most turbopump configurations. In turn, this configuration does not have any gyroscopic momentum.

Layout #3 shows the slightly lower compactness values, however, provides a minimal mass of connecting pipes.

It is seen from the results that utilization of turbopump configuration #1 and engine layout #3 provides the minimal mass of engine including fuel mass required to drive turbopump.

The configuration #6 has a maximal value of specific impulse among all the other ones. The closest by specific impulse configuration is configuration #1. It has 0.04 s lower specific impulse than configuration #6. However, configuration #1 was nevertheless determined as the best one taking into account the difference in mass of the turbopump (11.97 kg vs 12.40 kg) and mass of pipes (0.69 kg vs 1.095 kg), which are both smaller for configuration #1.

Analyzing the results, it is clear that the specific impulse has the highest impact on the mass creation, but for cases with small differences in specific impulse the consideration of the difference in mass of turbopumps and engine layout optimization, minimizing the pipes mass allow making a more comprehensive selection of the best configuration.

It should be noted that the utilization of an integrated system for engine layout creation takes about 1 minute accounting for the checking of the best solution that was found by the optimization approach. The total number of checked configurations consists of 27 variants (3 engine layout on 7 turbopump configurations) and time required is about 30 minutes. Estimated time for the non-automated execution of all processes covered by the integrated system will is about 1,620 minutes that is more than 50 times longer. Such a significant difference in development time leads to a significant reduction of the required labor time and number of engineers required to perform the comprehensive preliminary engine design. Also it opens the opportunity to perform quick feasibilities to explore new business cases.

OFF-THE-SHELF SOFTWARE TOOLS UTILIZED IN THE STUDY

The AxSTREAM®[9] turbomachinery design, analysis, and optimization tool was used for turbomachinery preliminary design.

The AxSTREAM NET™[8] 1D hydraulic networks analysis tool was used for leakage flows simulation during turbopump design and nozzle cooling simulation based on a parameterized model during the current study.

The AxSTREAM Rotor Dynamics™[10] and AxSTREAM Bearings™ were used for rotor dynamics and bearings simulation.

The AxSTRESS™[11] was used for preliminary stress analysis of turbomachinery components.

The AxSTREAM ION™[12] system engineering infrastructure for the design of engineering systems was utilized for the development of the turbopump preliminary design algorithm, including operation flowchart design, integration of the off-the-shelf and custom software tools, and execution.

SolidWorks[13] was used to create parameterized models of turbopump and engine in general.

ACKNOWLEDGMENTS

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CONCLUSIONS

1. Integrated approach which allows automatically performing a joint turbopump-engine layout preliminary geometry generation and selection of the best engine configuration taking into account multiple criteria and constraints was developed.
2. Three layouts of the engine and seven configurations of the turbopump were considered and the best combination of layout and turbopump configuration including their optimum interposition were found.
3. The configuration #6 has a maximal value of specific impulse among all the other ones. The closest by specific impulse configuration is configuration #1. It has 0.04 s lower specific impulse than configuration #6. However, configuration #1 was nevertheless determined as the best one taking into account the difference in mass of the turbopump (11.97 kg vs 12.40 kg) and mass of pipes (0.69 kg vs 1.095 kg), which are both smaller for configuration #1.
4. The specific impulse has the highest impact on the mass creation, but for cases with small differences in specific impulse the consideration of the difference in mass of turbopumps and engine layout optimization, minimizing the pipes mass allow making a more comprehensive selection of the best configuration.
5. The utilization of an integrated system for engine layout creation takes about 1 minute accounting for the checking of the best solution that was found by the optimization approach. The total number of checked configurations consists of 27 variants (3 engine layout on 7 turbopump configurations) and required time-consuming is about 30 minutes. Estimated time for non-automated execution of all processes covered by the integrated system will is about 1,620 minutes that is more than 50 times longer. Such a significant difference in development time leads to a significant reduction of the required labor time and number of engineers required to perform the comprehensive preliminary engine design. Also it opens the opportunity to perform quick feasibilities to explore new business cases.

[1] https://www.aurecongroup.com/expertise/digital-engineering-and-advisory/defining-digital-engineering

[2] Borisov V.A. Construction of main agregats and systems of rocket engines, Samara, 2011, 115 p.

[3] Huzel D. K., Huang D. H., Modern Engineering for Design of Liquid-Propellant Rocket Engine, Progress in Astronautics and Aeronautics, Volume 147, AIAA

[4] Moroz L.I., Burlaka M.V., Barannik V.S., Modern approach to liquid rocket engine development for microsatellite launchers, 34th Space Symposium, 2018

[5] Dobrovolsky M.V., Liquid rocket engines. Basics of design: university textbook. M:MSTU Bauman, 2005, pp. 254-257

[6] https://www.grc.nasa.gov/www/CEAWeb/

[7] Gahun G.G., Baulin V.I., Volodin V.A., Construction and desin of liquid rocket engines, M.: Machine construction, 1989, pp.265

[8] SoftInWay Inc, 2016, AxSTREAM NET™ user documentation.

[9] L. Moroz, Yu. Govoruschenko, P. Pagur, A uniform approach to conceptual design of axial Turbine / compressor flow path, The Future of Gas Turbine Technology. 3rd International Conference, October 2006, Brussels, Belgium.

[10] SoftInWay Inc, 2015, RotorDynamics™ user documentation.

[11] SoftInWay Inc, 2013, AxSTRESS™ user documentation.

[12] SoftInWay Inc, 2017, AxSTREAM ION™ user documentation.