Bulgarian Academy of Sciences. Space Research and Technology Institute.
Aerospace Research in Bulgaria. 36, 2024, Sofia

DOI: https://doi.org/10.3897/arb.v36.e14

REUSABLE AND LOW-COST SPACE ROCKET ENGINE WITH HIGH-EFFICIENT PROPELLANT PUMP

Abbasali Saboktakin*[1]*, Mohammad Monjezi

[1]*Ass. Professor, Department of Aerospace Engineering, İzmir Economic University, Turkey*
e-mail: abbasali.saboktakin@ieu.edu.tr, Alaptakin@gmail.com

Keywords: *Engine, Rocket, Piston Pump, Propellant, Finite element modeling.*

Abstract

Space propulsion mainly uses reciprocating pumps that are fully integrated with small-scale applications. In this paper, the specific specifications and designing factors that should be met by rocket engine fuel pumps are demonstrated, and a comparative study is formed of the suitableness of all the necessary kinds of pumps to be used with rocket engines and their applications. Furthermore, it examines a piston pump intended to refuel the liquid fuel nozzles. Due to the performance of this pump, different parts and its performance have been evaluated. The design of the pump is discussed such that after completing the design steps according to the pump performance, a numerical solution of the stress and strain applied on the inner wall of the cylinder is performed according to its performance under internal pressure. Then, considering the consistency of the body material and the same pressure and heat applied to the cylinder and piston, a sample of the cylinder and piston is analyzed in finite element modeling technique and the modeling results obtained from the simulation are presented.

Introduction

The development efforts of the main engine for the space vehicle were initiated in 1971 by NASA. Rockwell's Rocket dyne division as the prime contractor with NASA, after several years of development and testing, three space shuttles delivered to the space transportation system [1]. All space vehicles included high performance, perfect thrust, and high reliability and reusability systems. The simplest manner to differentiate rocket engines is to categorize them based on their technique of propellant pressurization and delivery [2]. All rocket engines can generally be divided into two categories: pressure-fed and pump-fed. While small-pressure engines use pressurized tanks for propellant delivery, the majority of rocket engines use turbo pumps that allow the propellants to be delivered to the desired pressure level. The pressure-fed engine is a self-pressurization such that self-pressurization is usually carried out through mono-propellant rocket engines and is obtained through the thermal decomposition of the liquid propellants or its vaporization. Pressure-fed system engines usually use high-pressure helium bottles.

In any case, the thrust stage of pressure-fed engines is confined through the tank technology [3]. An instance of these engines is the ARIANE 5G and AESTUS engines. Pump-fed engines use a turbo pump to increase the propellant pressure. In fact, some of the propellants are fed into a gas generator, which typically works at a necessarily high-pressure level. Modern liquid rocket engines have required pumping systems to transfer the propellant to the rocket engine [4, 5]. These pumps decrease the mass and size of other hardware by using lightweight high-pressure thrust chambers while decreasing the pressure of the liquid tank and minimizing the storage of inert gas. Figure 1 shows typical rocket engines that use high-performance pumping systems.

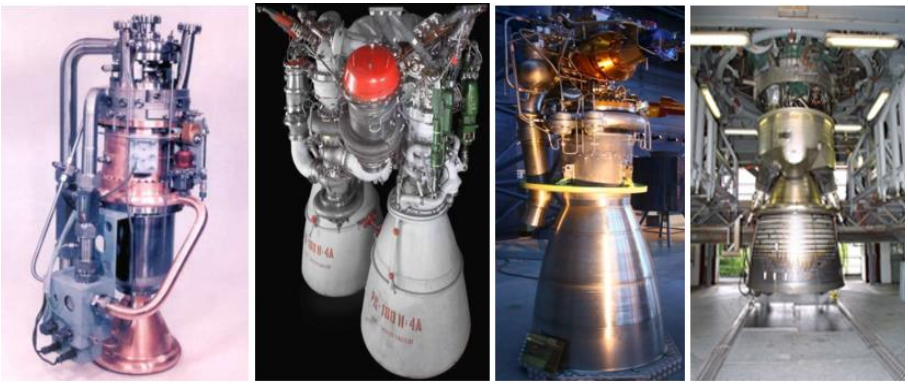


Fig. 1. Modern liquid rocket engines with high reliability and reusability. From left to right: P111 engine, RD-180, Viking engine, Vulcain 2 engine [2, 3].

The diverse use of piston pumps for different liquid rocket propulsion systems may be found as shown in Fig. 2. The most adaptable usage of a piston pump is on a satellite that has to make multiple and massive ΔV maneuvers. Any polar orbit satellite and geostationary satellite could have enormous ΔV maneuver requirements [6]. Since polar satellites and geostationary satellites are commonly high-priced and need to perform for several years, they constitute likelihood applicants for performance improvements [7]. However, it must be referred to that the performance supplied using a solid booster could, in a few cases, exceeds the overall performance of a bipropellant liquid rocket. The simplest improvement is that the piston pump can offer on/off functionality and throttling as well [8, 9]. Other applications are probes to the moon, interplanetary probes, and near-earth objects that commonly require enormous ΔV maneuvers. These specific missions have mass budgets and may benefit from any weight reduction and financial savings while overall performance stays high. Finally, missions to or from the other planets surface, moons will also benefit from overall performance enhancements.

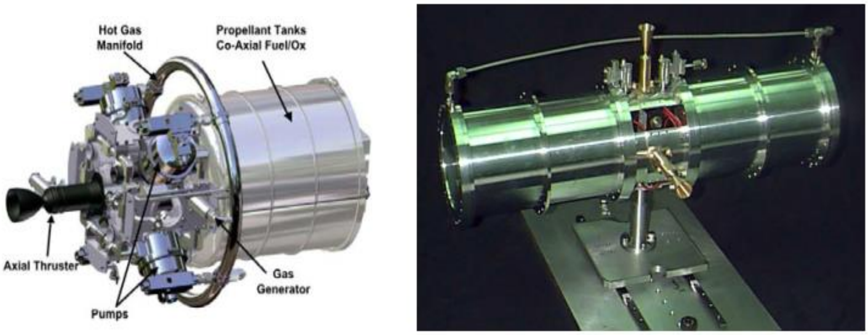


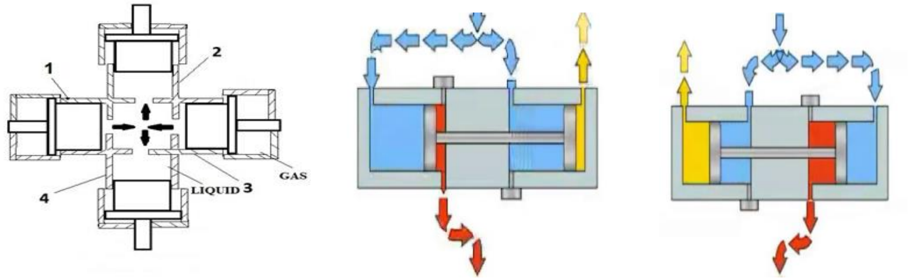
Fig. 2. Pump-fed propulsion system in satellite [8]

The design of the pump, as well as the representation of the fluid, inside the pump, is very difficult, time consuming and costly [10–13]. Compact Fluid Analysis (CFD) is the best available tool for analyzing flow patterns inside the piston pump and gas generator to predict their behavior under different operating conditions. It also helps optimize pump design parameters by providing the most correct flow patterns along with more efficient pump operation [14,15].

The objective of this paper is to survey the status of research in the areas of pumps for liquid rocket engines in order to provide a comprehensive review of the state of the art and understanding of important challenges. In this article, the emphasis will be on a reciprocating pump and the pump pistons are stimulated by gas. We use a gas generator to convert the liquid fuel of the peroxide to the gas with the pressure and temperature. We analyzed the pump and also the generator in the finite element modeling software, and the results are expressed to give complete awareness of how to use it in different situations. The research will concentrate on the design and development of a 300-gram pump capable of delivering fuel and oxidizer at 5 MPa for a 1000-N engine with remaining tank pressure at 0.35 MPa.

Pump design

The pump contains four cylinders and pistons that are joined together, as shown in Fig. 3. It has a central section that provides the pump with a liquid inlet from the propellant tank and directions reflect the flows of the inlet and outlet depicted in Fig. 3a. The liquid propellant's inlet port is the large port at the middle of Fig. 3b, and a separate outlet hole is on the opposite side of the piston pump that is evident in Fig. 3a. The gas is distributed and operated by valves to the outer cylinders. Liquid cylinders are smaller in diameter than gas cylinders. The area ratio allows the reciprocating pump to be operated by means of delivered propellants. At the end of every cylinder, the gas cylinder is larger in diameter than the liquid cylinder and the gas entry point. A piston separating the fuel and gas chambers is located among them. As seen in the pump schematic, it is understood that no shaft or other rotating components are required to apply gas pressure to the rocket liquid. The gas inlet valves are retained to cancel the mass effect of movement, so that the opposite movement of pistons is towards or away from each other. Furthermore, because of the existing pistons in pump chambers, the control scheme is considered to compensate for the pressure loss. According to Fig. 3a, cylinder numbers 1 and 3 reach the end of the stroke, while cylinders 2 and 4 have been refilled with the propellant. A control mechanism provides the continuation of the flow such that cylinders 2 and 4 are pressurized with gas before reaching pistons 1 and 3 to their limit and venting their cylinders.



a) *b)* *c)*

Fig. 3. a) Primary schematics of the piston pump; b)&c) Preparation of fuel injection from propellant tank to engine chamber occurring within the reciprocating pump.

This pump weighs 470 grams, and the blocks and cylinders are all made of aluminum, with the exception of the valves and tubes. The role of curved pipes is to send gas to the inlet valves shown in Figure 4 are used in the design of light alloy metals. The largest hole located in the centre of the block is the fuel entry site, and the exit point of the four small holes is situated in the middle of the pump and on the other side. Each cylinder has a perfect displacement of 8 cc between the piston stops, or 32 cc per pump cycle. The valve opening time for fuel input is also less than 10ms, and this is independent of the piston speed. In order to provide the required force to drive the pistons, a key aspect previously mentioned is that the diameter of the gas cylinder is greater than that of the liquid cylinder. The gas and liquid cylinders are not combined but are connected by screws. This pump works at a far higher pressure than those pumps used in conventional launchers.

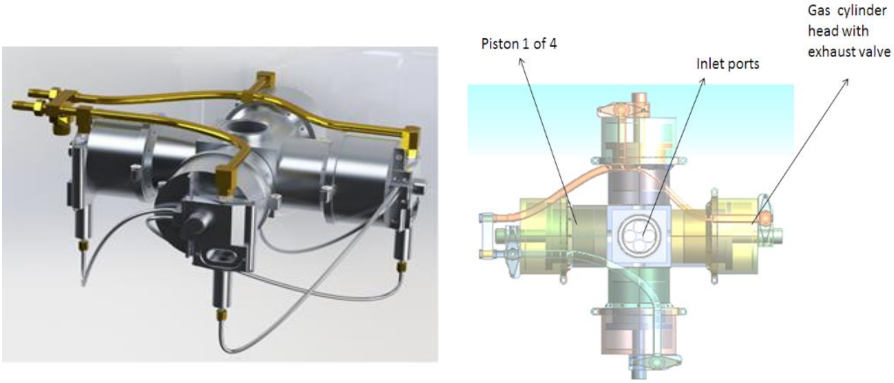


Fig. 4. The primary design of the reciprocating pump

As mentioned earlier, this pump does not use any shafts to move the pistons and power transmission. However, in order to move the pistons, we used a pneumatic valve to control the inlet and outlet valves. As shown in Fig. 4, a tap is located at the bottom of each piston. In fact, this valve is driven by the gas used in the system to open and close the gas inlet and outlet. This will control the movement of the pistons in the system and cause the pistons to always move against each other. In addition, such controls reduce friction and damage in the system. Because it causes injection before the piston reaches the end of the motor cycle to prevent its collision with the body. Each cylinder has a standard displacement of 7 cm between the start of motion and the piston stroke per pump cycle. The opening time for the fuel valve is about 9 ms, which is independent of the piston speed.

Investigation of stress and strain of cylinder and piston

One of the important things to keep in mind is that the pump is subject to high internal pressure, which requires careful consideration in its design due to the low thickness of the cylinder wall. Here, we examine the stresses and strains of the cylinder and piston based on the applied pressure and then simulate it using finite element modeling. In Fig. 5, there is a cylinder and a piston. One side is the fuel inlet and outlet, and the other is the gas inlet and outlet valves. The fuel inlet pressure enters the cylinder and moves the cylinder upwards. When the piston reaches a high point, the valve opens and the pressure gas enters the cylinder, causing the piston to move downward and leave the fuel outlet.

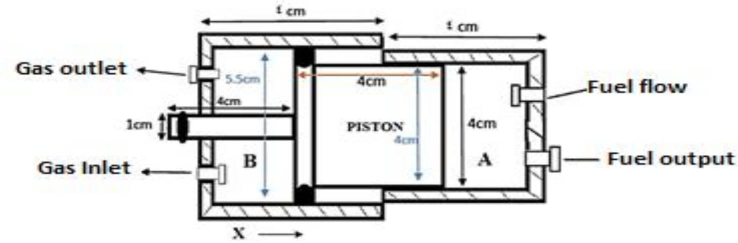


Fig. 5. Pressure cylinder and piston

We also use the specifications given in Table 2 to solve the problem.

Table 1. Pump specification

Fuel inlet pressure	1 MPa
Inlet gas pressure	4 MPa
Output fuel pressure	4 MPa
The thickness of the cylinder walls	3 mm
Speed of opening and closing of valves	9 ms
Diameter of inlet and outlet valves	5 mm

Numerical Problem Solving:

The first step in calculating the stress and strain of the cylinder is to examine its thin or thick wall. If we call the cylinder thickness t and the inner diameter of the cylinder din, we classify the cylinders according to the value [16]:

(1) $$a = \frac{t}{d_{in}}$$

It will be done. If the value a is less than 20.1, we call the cylinder a thin wall, otherwise the cylinder is a thick wall. There are different opinions on the boundary value of a. It can be larger than 20.1 (such as 0.5 or 0.2), but it should be noted that the smaller a is, the more accurate the calculations for the thin wall cylinder are. A condition of 1/20 for the value of a gives the results with acceptable accuracy. So, the first step in calculating the stress and strain of the cylinder is to check whether the wall is thin or wound [17].

According to the formula given for both sides of the cylinder is obtained.

$$a_A = \frac{0.003}{0.04} = 0.075;$$

$$a_B = \frac{0.003}{0.055} = 0.054.$$

So, the first and second parts of the thin wall cylinder are assumed. We now turn to problem calculations.

Longitudinal Stress in Cylinders

To obtain the longitudinal stress of the cylinder, we use the following formula:

(2) $\sum F_X = 0;$

(3) $\partial_x(2\pi rt) = P\ (\pi r^2) \rightarrow\ \partial_x = \partial_L = \frac{Pr}{2t} = \frac{Pd}{4t}.$

According to the above formulas, the longitudinal stress for both sides of the cylinder is calculated as follows.

$$\delta_{lA} = \frac{5000000\times 0.04}{4\times 0.003} = 150 \text{ Pa};$$

$$\delta_{lB} = \frac{4000000\times 0.055}{4\times 0.003} = 165 \text{ Pa}.$$

Environmental Stress in Cylinders

The environmental stress of the cylinder is obtained from the following relationship.

(4) $\sum F_y = 0;$

(5) $\partial_y(2Lt) = P\ (2rL) \rightarrow\ \partial_y = \partial_h = \frac{Pr}{t} = \frac{Pd}{2t}.$

The environmental stresses obtained are as follows.

$$\delta_{hA} = \frac{5000000\times 0.04}{2\times 0.003} = 300 \text{ Pa};$$

$$\delta_{hB} = \frac{4000000\times 0.055}{2\times 0.003} = 330 \text{ Pa}.$$

The radial stress in the first and second parts of the cylinder is assumed to be zero due to its thin wall.

Shear Stress at 45 and 60 Degrees:

We use the following formula to obtain the stress at angles of 45 and 60 degrees on both sides of the cylinder.

(6) $\tau_\theta = \frac{1}{2}(\partial_x - \partial_y)\sin 2\theta.$

Part A cylinder with a degree angle.

$\tau_\theta = 0.5 \times (|150 - 300|)\sin 2 \times 45 = 0.5 \times 150 = 75$ Pa.

Part A cylinder with a 60-degree angle.

$\tau_\theta = 0.5 \times (|150 - 300|)\sin 2 \times 60 = 0.5 \times 150 \times 0.866 = 64.95$ Pa.

Part B with a 45-degree angle.

$\tau_\theta = 0.5 \times (|165 - 330|)\sin 2 \times 45 = 0.5 \times 165 = 82.5$ Pa.

Part B cylinder with a 60-degree angle.

$\tau_\theta = 0.5 \times (|165 - 330|)\sin 2 \times 60 = 0.5 \times 165 \times 0.866 = 71.445$ Pa.

The strain on the cylinder

The longitudinal strain for both sides of the cylinder is obtained from the following relation:

(7) $\varepsilon_x = \frac{1}{E}(\delta_X - \vartheta\delta_y).$

E is a modulus of aluminum elasticity, which is 69 GPa, which after conversion to Pagal is considered to be 69×10^9 and is a fixed number.

Therefore, the longitudinal strain for Part A of the cylinder is equal to

$\varepsilon_{xA} = \frac{1}{69\times10^9}(150 - 0.32 \times 300) = 14 \times 10^{-10}.$

Also, for Part B cylinder is equal to

$\varepsilon_{xB} = \frac{1}{69\times10^9}(165 - 0.32 \times 330) = 23 \times 10^{-10}.$

Cylinder peripheral strain

The strain created in the cylinder environment is obtained using the following equation:

(8) $\varepsilon_y = \frac{1}{E}(\delta_y - \vartheta\delta_x)$

According to the stated relation, the strain created in Part A is a cylinder.

$$\varepsilon_{yA} = \frac{1}{69\times10^9}(300 - 0.32 \times 150) = 3.64 \times 10^{-9}.$$

And for Part B cylinders too

$$\varepsilon_{y1} = \frac{1}{69\times10^9}(330 - 0.32 \times 165) = 4 \times 10^{-9}.$$

The radial strain is zero because the thin cylinder wall is assumed.

The stress on the piston

$$\sigma_A = \frac{F_2}{A_2} = P_2 = 5 \text{ MPa}; \tag{9}$$

$$\sigma_B = \frac{F_1}{A_1} = P_1 = 4 \text{ MPa}. \tag{10}$$

The strain on the piston

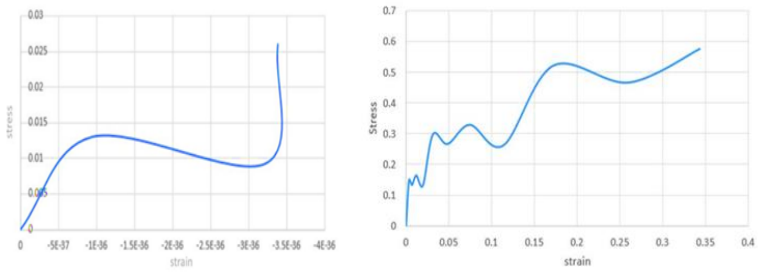
$$\varepsilon_A = 5 \times 10^6 \times 69 \times 10^9 = 345 \times 10^{15};$$

$$\varepsilon_B = 4 \times 10^6 \times 69 \times 10^9 = 276 \times 10^{15}.$$

Modeling results

The results for the stress and strain of the cylinder and piston according to the pressure exerted on the inner wall of the cylinder using finite element modeling are as follows.

By taking the stress and strain outputs from a node and drawing the diagram for it, the strain diagram of the cylinder can be obtained. Fig. 6 depicts the strain diagram of a node in directions X and Y.



a) *b)*

Fig. 6. Stress and strain diagram of the cylinder in direction of: a) X and b) Y

As shown in Fig. 7, the highest and lowest stresses on the cylinder can be observed in the finite element results. The maximum stress in the body is 1136 MPa.

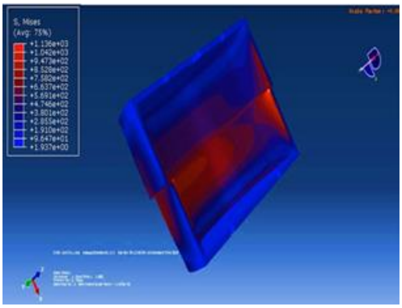
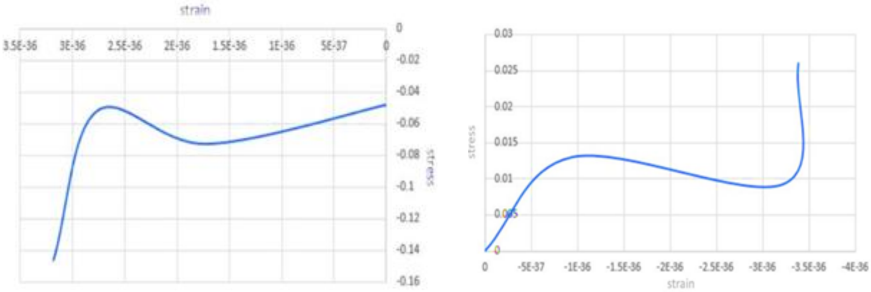


Fig. 7. Stress on the inner wall of the cylinder

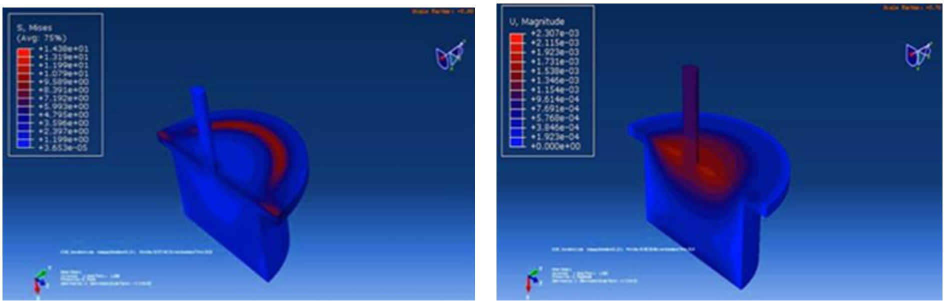
The same steps are then repeated for the piston and the results are shown in Fig. 8.



a) *b)*

Fig. 8. Stress and strain diagram of the piston in direction: a) X and b) Y

The maximum stress and strain in the piston is as shown in Fig. 9.



a) *b)*

Fig. 9. a) Maximum and minimum stresses on the piston b) The strain applied to the piston

Conclusion

The space rocket consists of a number of subsystems and has been designed to maximize safety, simplicity, and redundancy in all respects. By keeping the fuel injection using the reciprocating pump as an important device, the results indicate that there are fewer modes of failure than with other pumps. A series of stress and flow analyses for the pump were performed using ANSYS, and stress and pressure distributions were recognized. In order to confirm the accuracy of our modeling results, comparisons with experimental results were performed, and a very good agreement was found. Future development work will be performed through other pump design factors of importance will be factored in such as the materials' properties and determine the heating of various pump components, as well as any subsequent thermal stresses.

References

1. Wofford, S., J. Fred Jue, J. Cook, Space Shuttle Main Engine Design Evolution, 57th Joint Army-Navy-NASA-Air Force Propulsion Meeting / 5th Liquid Propulsion Subcommittee Meeting. Colorado Springs, CO. May 3-7, 2010.
2. R. Biggs, Space Shuttle Main Engine: The First Twenty Years and Beyond. American Astronautically Society History Series, Volume 29. Univelt for American Astronautical Society, San Diego, CA, 2008.
3. Betts, E., R. Frederick, R. A., Jr.: A Historical Systems Study of Liquid Rocket Engine Throttling Capabilities, AIAA Paper 2010-6541, 2010.
4. U. Barske, High Pressure Pumps for Rocket Motors. Rocket Propulsion Department, Wescott. August 2016.
5. R. Albat, G. Langel, O. Haidn, Handbuch der Raumfahrttechnik, Hanser Verlag, 2007.
6. EOPortal Directory: All-Electric Propulsion and Multi-Satellite Launch System for Communication Satellites, 2020.
7. D. Lev, et al., The technological and commercial expansion of electric propulsion in the past 24 years. In Proceedings of the 35th International Electric Propulsion Conference, Atlanta, GA, USA, 8–12 October 2017.
8. Z. Rosenberg, Xcor tests piston pump-fed rocket engine, August 2016.
9. B. Campen, Liquid oxygen piston pump ready for reusable space flight, April 2017.
10. J. C. Whitehead, Propulsion Engineering Study for Small-Scale Mars Missions, UCRL-CR-122442, Univ. of Calif. Lawrence Livermore National Lab, September1995.
11. J. C. Whitehead, United States Patent, Patent Number: 5,026,259 , Date of Patent: Jun. 25, 1991.
12. J. C. Whitehead, Mars ascent propulsion options for small sample return vehicle , May 12, 1997.
13. M. A. Corbo and Stearns, Ch. F., Practical design against pump pulsations, Proc. 22nd International Pump Users Symposium, 2005.
14. J. C. Whitehead, Hydrogen Peroxide Gas Generator Cycle with a Reciprocating Pump, AIAA Paper 2002-3702, July 2002.

15. M. Ventura, Novel Concepts for an Advanced Non-Toxic Gas Generator, 42nd AIAA/ASME/ SAE/ASEE Joint Propulsion Conference & Exhibit Sacramento, CA, July 9-12, 2006.
16. E. J. Hearn, Mechanics of Materials 2: The mechanics of elastic and plastic deformation of solids and structural materials, Butterworth-Heinemann, 1997.
17. G. P. Sutton and O. Biblarz, Rocket Propulsion Elements, Wiley, 2001.

КОСМИЧЕСКИ РАКЕТЕН ДВИГАТЕЛ ЗА МНОГОКРАТНО ИЗПОЛЗВАНЕ НА НИСКА ЦЕНА, ОБОРУДВАН С ВИСОКОЕФЕКТИВНИ ПОМПИ

А. Сабоктакин, М. Монджези

Резюме

Космическото задвижване използва главно бутални помпи, които са напълно интегрирани с малките приложения. В тази статия са демонстрирани специфичните спецификации и конструктивни фактори, на които трябва да отговарят горивните помпи за ракетни двигатели, и е направено сравнително проучване на пригодността на всички необходими видове помпи, които да се използват с ракетни двигатели и техните приложения. Освен това се изследва бутална помпа, предназначена за зареждане на дюзите за течно гориво. Поради производителността на тази помпа са оценени различни части и нейната производителност. Дизайнът на помпата се обсъжда така, че след завършване на проектните стъпки в съответствие с производителността на помпата, численото решение на напрежението и деформацията, приложени върху вътрешната стена на цилиндъра, се извършва в съответствие с нейната производителност при вътрешно налягане. След това, като се има предвид плътността на материала на тялото и същото налягане и топлина, приложени към цилиндъра и буталото, проба от цилиндъра и буталото се анализира с техника за моделиране с крайни елементи и се представят резултатите от моделирането, получени от симулацията.