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# INFLUENCE OF PROPELLANT LEAKAGE FROM PUMP AREA INTO TURBINE AREA ON TURBO-PUMP OPERATION STABILITY

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*There is an increasing trend to liquid-propellant rocket engines which run on eco-friendly storable propellant. This trend is mostly dictated by the refusal to use traditional toxic storable propellant in many countries. The most widespread eco-friendly storable propellant is hydrogen peroxide with kerosene. Though, this propellant has a lower specific impulse in comparison with traditional liquid oxygen with kerosene. To compensate the loss of specific impulse, there is a reason to design a staged combustion engine. Evidently, the turbopump is the most complicated system in the staged combustion propulsion system. This fact makes research devoted to turbo-pumps a top priority. The paper aims to determine the influence of propellant leakage from the pump area into the turbine area and create recommendations which would allow organizing the stable operation of turbopump. As a result of turbopump staged combustion cycle testing, a conclusion had been made that leakage, which opens during the test, significantly influences the stability of turbopump operation. Depending on the amount of leakage, the turbine generated power drop was between 20 and 45 %, which led to a decrease in rotation speed and outlet pressure of the pump. During the R&D process, a way of leakage influence elimination had been offered. Formulated recommendations may be used during the design process of the turbopump for staged combustion liquid propulsion systems.*

***Keywords:*** *Hydrogen peroxide, leakage, operational stability, turbo-pump, rocket engine, mechanical sealing.*

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## INTRODUCTION

Recently in the world there has appeared a steadily growing interest in liquid propulsion systems, which operate on environmentally friendly storable propellant. This is mainly due to the refusal of traditional toxic propellant components in many countries [4]. Another important trend in the development of propulsion systems is the necessity to reduce either the development and operational costs of launch vehicles, which makes storable ecologically friendly propellant the most attractive. The most widespread pair of components for such type of propellant is hydrogen peroxide with kerosene [1].

The only drawback of this propellant is a relatively low specific impulse in comparison with the cryogenic propellant like liquid oxygen with kerosene. However, this disadvantage can be easily compensated by using the staged combustion cycle. In this case, an insignificant complication of the engine design will make it possible to create a liquid rocket engine with specific characteristics even higher than the liquid rocket engine, which runs under the gas generator cycle on

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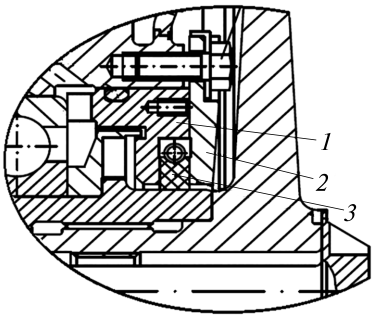

***Fig. 1.*** Sealing unit of the RD 861K rocket engine turbopump: *1* — seal housing, *2* — cover, *3* — graphite gas ring

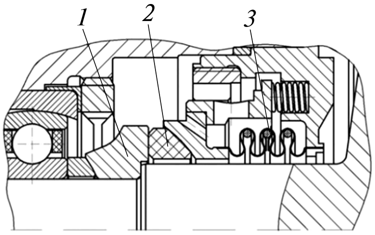

***Fig. 2.*** Sealing unit of RD 858 rocket engine turbopump: *1* — support sleeve, *2* — graphite semi-spherical ring, *3* — bellows

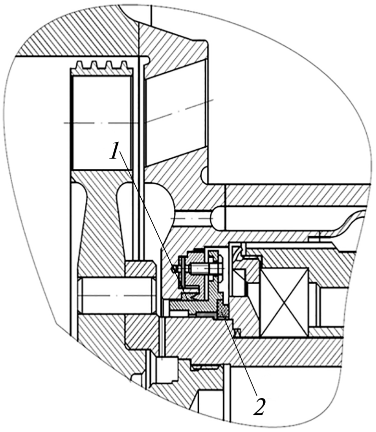

***Fig. 3***. Sealing unit of the RD 123K rocket engine turbopump: *1* — aluminum cuff, *2* — graphite ring

liquid oxygen and kerosene [6]. Moreover, there are other advantages of the staged combustion cycle, such as simplicity of the start mode organization [3] and the possibility of its regulation in a wide range [2].

The most complex and knowledge-intensive unit in staged combustion liquid-propellant rocket engine is a turbopump unit. Due to its energy intensity, high pressure at the outlet of the pumps, and high rotation speed, it is rather difficult to make its operation stable.

## FORMULATION OF THE PROBLEM

This article aims to describe the reasons for the unstable operation of the turbopump during tests using mathematical modeling. Another purpose is to propose a solution to stabilize the turbopump operation. In this case, the term "instability" of turbopump operation should be understood as a spontaneous fall of its operational mode due to the influence of various internal factors such as leaks between cavities, the influence of axial forces, or mechanical contact of rotor parts with the stator parts.

As soon as necessary changes to ensure the stability of the turbopump are applied, their relevance should be verified in the test. According to its results, it will be possible to conclude about the consistency of the proposed theory and the efficiency of the applied changes, which should eliminate the negative influence of internal factors on the operating mode of the unit.

## REVIEW OF THE LITERATURE

In the XX century, the space industry had accumulated huge experience in the organization of seals between the cavities of pumps and turbine for turbopumps of engines, which run either under gas generator cycle or oxidizer rich gas staged combustion cycle.

Consider the seal between the cavities of the pump and the turbine. The boundary condition is the same pressure from the pump and the turbine cavities. In this case, it is preferable to use a split gas ring made of graphite in order to seal these cavities. In figure 1, a sealing unit of the RD 861K rocket engine turbopump is shown [8].

For the most important places, such as a cavity between the oxidizer pump and the turbine, which is driven by fuel-rich gas, mechanical seals made of graphite are applied. In figure 2, the sealing unit of the RD 858 rocket engine turbopump is presented [7].

Turbopumps designed for rocket engines, which run under a staged combustion cycle, have a much more complicated sealing block between the pump and the turbine. The reason for this is the significant pressure drop between an oxidizer pump cavity and a turbine cavity in addition to high rotation speed and high temperature from the turbine side. This pressure drop is equal to the difference between pump outlet pressure and turbine inlet pressure. In existing staged combustion rocket engines, this pressure drop may rich 50 % to 100 % of total pump outlet pressure. This fact makes it almost impossible to seal these cavities totally.

Usually, in turbopump units for rocket engines, which run on liquid oxygen and kerosene, sealings with guaranteed leakage of liquid oxygen into the turbine cavity are designed.

In figure 3, a sealing unit of the RD 123K rocket engine turbopump is shown [5].

The idea of this seal operation is in providing tightness between the oxidizer pump cavity and the turbine cavity during the preparation process, such as the evacuation of the gas from the pipes and filling them up with propellant. However, as soon as the pressure at the pump outlet rises, the sealing opens like a valve, and as a result, a stable leakage of liquid oxygen into the turbine cavity appears. Taking into account that in rocket engines liquid oxygen is a supercritical fluid, this leakage does not lead to the change of turbopump parameters.

Mechanical seals are the most reliable type of sealing, but even they do not provide 100% tightness in such difficult conditions. Moreover, applying this type of sealing is connected with a number of technological and logistical difficulties such as:

- limited amount of raw material suppliers;
- welding issues of bellows with thin walls;
- a significant increase of axial dimensions of the unit.

Taking into account that even this type of sealing does not provide 100 % tightness in such harsh operational conditions, it is reasonable to consider an easier design of the sealing block, which would provide tightness during launch preparation processes.

## METHODOLOGICAL ASPECTS OF TURBOPUMP PARAMETERS' STABILIZATION

Considering that hydrogen peroxide is a non-aggressive storable oxidizer, the design of the sealing block may be significantly simplified. The traditional combination of a rubber O-ring with a supporting fluoroplastic ring had been applied. The main idea of this sealing block is to provide tightness by means of the rubber O-ring during the preparation process. As soon as the operation of the turbopump is started, it was expected that the rubber O-ring would wear out in a short period of time causing the leakage of hydrogen peroxide, which would be restricted by a floating ring. In this case, the amount of leakage will be determined by the gap between the floating ring and the rotor. In figure 4, the chosen sealing unit design is shown.

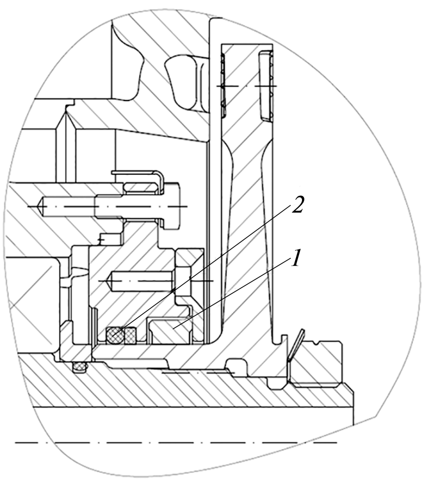

***Fig. 4.*** Chosen sealing unit: *1* — floating ring, *2* — rubber O-ring with the supporting fluoroplastic ring

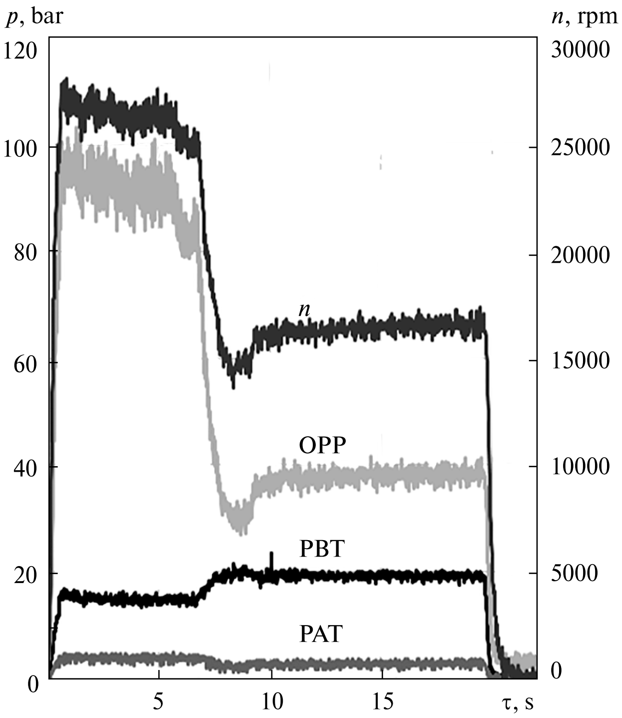

***Fig. 5.*** Main operational parameters of the turbopump: PBT — pressure before the turbine, PAT — pressure after the turbine, OPP — oxidizer pump pressure

During the set of turbopump tests, a rapid drop of rotation speed was being registered as soon as the rubber O-ring was worn out. In figure 5, the diagram

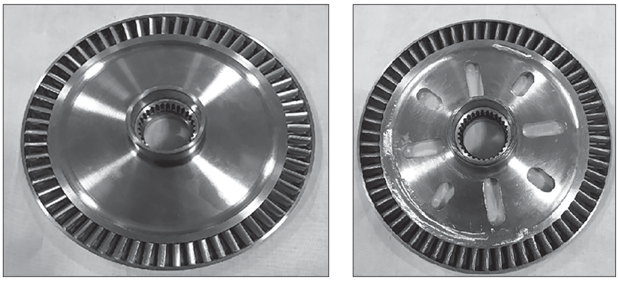

***Fig. 6.*** Turbine wheel before and after upgrade

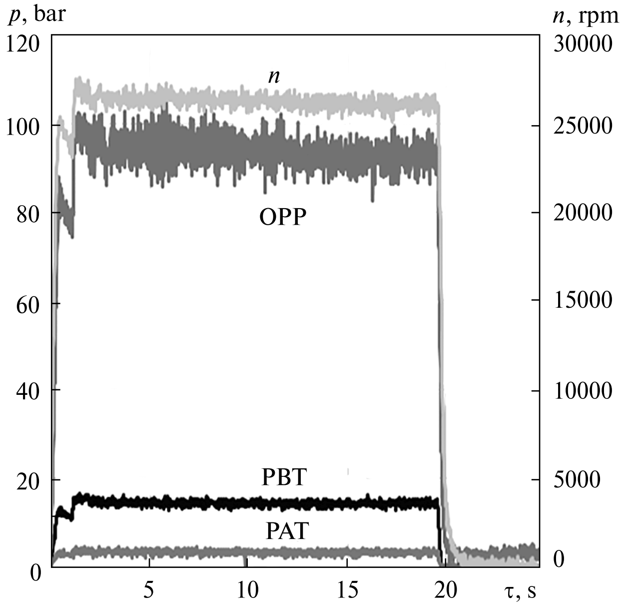

***Fig. 7.*** Main operational parameters of the turbopump after the upgrade: PBT — pressure before the turbine, PAT — pressure after the turbine, OPP — oxidizer pump pressure

with the main operational parameters of the turbopump, which were registered during tests, is presented.

As it is shown in figure 5, after the 8th second of the test, a rapid change of the turbopump operation mode took place. The drop of the turbopump rotation speed was 38 % in relation to the initial mode. Analysis of the parts of the rotor and stator of the turbopump and mathematical modeling made it possible to conclude that the reason for a mode change was an open leakage from the oxidizer pump cavity into the turbine cavity.

To explain the physical reason for the rapid drop of the operational mode, the mathematical model which describes the operational process of the turbine was created. The main equation in this model was the mass conservation law, expressed in integral form:

$$\dot{m}_t = \frac{F_t p_{BT}}{\sqrt{RT_{AT}}}\sqrt{\frac{2k}{k-1}\left[\left(\frac{p_{AT}}{p_{BT}}\right)^{\frac{2}{k}} - \left(\frac{p_{AT}}{p_{BT}}\right)^{\frac{k+1}{k}}\right]},$$

$F_t$ — Square area of the turbine, $p_{\mathrm{BT}}$ — pressure at the turbine inlet, $RT_{AT}$ — specific energy capacity, $p_{AT}$ — pressure at the turbine outlet, $k$ — specific heat ratio.

The solution to the system of equations bundles the mass flow rate equation through stator blades, mass flow rate equation through rotor blades, and mass flow rate through the oxidizer pump, giving a physical description of the process. It follows that the cause of the drop of the operational mode was throttling of the rotor blades by the opened leakage. This led to a significant reduction of the turbine wheel throughput, which consequently caused a decrease in the gas mass flow rate. According to the mathematical model, the drop in power generated by the turbine corresponds to a 44 % reduction in turbine wheel throughput.

As a solution to this issue, it was proposed to arrange drainage from the cavity by making eight oval-shaped holes in the turbine wheel neck. This solution should prevent the oxidizer from entering the blades of the turbine wheel. In the upper part of figure 6, the turbine wheel in the initial condition is presented. The upgraded turbine wheel is presented in the bottom part of the same figure with milled oval-shaped holes for drainage of the oxidizer, which leaks from the pump cavity into the turbine cavity.

The main idea of this modification is to eliminate the leakage influence on parameters of the turbopump operation instead of dealing with the leakage itself. To verify this theory, a series of turbopump tests with the upgraded turbine wheel was performed. For the purity of the experiment, no other changes were implemented to the design of the turbopump. As a result of the experiment, a stable operational mode of the turbopump was achieved, which confirmed the initially put forward hypothesis. In figure 7, the diagram with the main turbopump parameters of the qualification test is presented.

From the test results, it follows that increasing the impulsivity of the turbine due to oval-shaped drainage holes ensures the complete elimination of the influence of leakage on the operational parameters of the turbopump. As a result, it allowed achieving the stable operation of the turbopump.

To estimate the influence of changes in the turbine impulsivity on the turbine efficiency, the estimation method, which is based on qualified pump parameters, was chosen.

Turbine efficiency was estimated according to the formula:

$$\eta_t = \frac{\dot{m}_p \Delta p_p}{\rho_p \eta_p L_{ad} \dot{m}_t},$$

$\dot{m}_p$ — mass flow rate of liquid through the pump, $\Delta p_p$ — pump head, $\rho_p$ — density of liquid in the pump, $\eta_p$ — efficiency of the pump, $L_{ad}$ — adiabatic velocity, $\dot{m}_t$ — gas mass flow rate through the turbine.

According to the method used for the efficiency estimation, it was determined experimentally that drainage holes in the turbine wheel caused a reduction of turbine efficiency by 1.5 % but allowed achieving the stable operation of the turbopump.

## CONCLUSIONS

The presented research allowed us to create the mathematical description of the physical process, which caused a rapid drop of generated power by a turbine running on decomposed hydrogen peroxide. Understanding these processes is critical for arranging of stable operation of the turbopump.

Along the way, mathematical, methodological, and structural decisions, which should provide stable operation of turbopump for such liquid-propellant rocket engine, have been offered.

Analysis of the research results shows that they could have significant practical value concerning the design process of turbopumps for liquid-propellant rocket engines running on hydrogen peroxide and kerosene:

1. Leakage of oxidizer on turbine wheel blades causes a reduction of throughput, which consequently leads to the significant drop in the generated power.
2. Drainage holes in the turbine wheel allow the eliminating of the influence of oxidizer leakage on the operational parameters of the turbopump.
3. The reduction of the turbine degree of reaction allowed arranging the stable operation of the turbine, causing a decrease in turbine efficiency. However, its influence on the overall efficiency of staged combustion rocket engine running on hydrogen peroxide is negligible.

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# ВПЛИВ ВИТОКУ КОМПОНЕНТА З ПОРОЖНИНИ НАСОСА В ОБЛАСТЬ ТУРБІНИ НА СТІЙКІСТЬ РОБОТИ ТУРБОНАСОСНОГО АГРЕГАТА

Останнім часом в світі стабільно зростає інтерес до РРД, що працюють на екологічно чистому паливі. Це зумовлено законодавчою відмовою багатьох країн від токсичних компонентів. Відомо, що найбільш поширеними висококиплячими екологічно чистими компонентами палива є пара перекис водню — гас. Однак двигуни, що працюють на цій парі компонентів палива, характеризуються нижчим питомим імпульсом ніж двигуни, що працюють на компонентах кисень — гас. Для компенсації цієї різниці доцільно проєктувати двигуни по схемі з допалюванням генераторного газу. Відомо, що турбонасосний агрегат (ТНА) є найбільш складним і наукомістким агрегатом у двигуні такої схеми. Цей факт робить актуальним наукові роботи, спрямовані на вивчення процесів у ТНА. Надзвичайно важливим є визначення впливу витоку компонента з порожнини насоса у порожнину турбіни і формування рекомендацій щодо організації стійкої роботи турбіни. В результаті натурних випробувань ТНА, спроєктованого для РРД з допалюванням генераторного газу, було виявлено, що витік з порожнини насоса у порожнину турбіни суттєвим чином впливає на стійкість роботи ТНА. Залежно від величини витоку спостерігалося падіння потужності, генерованої турбіною, від 20 до 45 %, що призводило до зниження обертів ротора турбонасосного агрегату, і як наслідок — до падіння тиску компонента на виході з насоса. В ході робіт було виявлено причину падіння потужності, що генерується турбіною, і були запропоновані способи зменшення впливу витоку на режим роботи ТНА. Сформовані рекомендації щодо зменшення впливу витоку компонента на режим роботи ТНА можуть бути застосовані для проєктування ТНА РРД з допалюванням генераторного газу.

***Ключові слова:*** перекис водню, виток, стійкість роботи, турбонасосний агрегат, ракетний двигун, стояночне ущільнення.