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Turbopumps for Gas Generator and Staged Combustion Cycle Rocket Engines

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The need to increase the engine specific impulse, lead design engineers to start development of closed cycle engines where gas is combusted in the main combustion chamber after passing through the Main Turbopump Assembly turbine. Trade-off study analysis for turbopumps of different cycles engines was performed for RD-0110 and RD-0124 LOX-kerosene engines, which have the same thrust range. The analysis included comparison of the parameters, design approaches, turbopumps design and development features for gas generator and stage combustion cycle engines.

I. Introduction

The first engines were developed in KBKhA using the open cycle, in which the turbopump turbine discharge gas was ducted outboard and wasn't used in the engine for additional thrust production. The need to increase the engine specific impulse, made design engineers to start development of closed cycle engines where gas is combusted in the main combustion chamber after passing through the Main Turbopump Assembly turbine. KBKhA has great experience in design of open and closed cycle rocket engines turbopumps. KBKhA developed their first turbopump in 1955. KBKhA developed 68 turbopumps for LOX-kerosene, LOX-LH2 rocket engines, for storable propellant engines and for the RD-0410 nuclear rocket engine. Thrust range for KBKhA`s engines with pump feed system is from 15 to 2000 kN. KBKhA`s engines were used in the "Vostok" and "Voskhod" boosters, which performed space exploration tasks, including the first manned space flight. KBKhA also developed the engines for "Soyuz" and "Proton" boosters, which have been in operation for 40 years. The design of the RD-0120 LOX-LH2 engine with 2000 kN thrust for the "Energia-Buran" multipurpose reusable space-launcher complex was a great success for KBKhA. KBKhA engines are currently used in the third stage of "Soyuz" booster, in the second and the third stage of "Proton" booster and in the first and the second stage of "Rokot" booster.

II. Major Milestones of KBKhA`s Rocket Engines Feed System Schemes

From 1955 till 1961 turbopumps were developed for gas generator cycle engines. From 1961 KBKhA develop engines, based on high-performance staged combustion cycle. Almost all subsequent engines designed by KBKhA were staged combustion cycle engines. Every new engine scheme requires a new approach to feed system design. The major milestones of KBKhA`s rocket engines feed systems are presented on the Fig. 1.

The maximum performance from closed cycle can be obtained at high combustion chamber pressure, which raises pressure throughout the engine, including at the turbopump outlet and turbine inlet. To reliably provide this increased pressure, the turbopump must be considered one of the primary engine development focuses.

Trade-off study analysis for turbopumps of different cycles engines was performed for RD-0110 gas generator and RD-0124 staged combustion LOX-kerosene engines, which have the same thrust range.

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Storable propellant rocket engines

▼1956	▼1961	▼1977
Gas generator cycle engines	**Staged combustion cycle engines**	
One main turbopump		
Without boost pumps	Oxidizer and fuel ejector boost pumps	Oxidizer and fuel turboaxial boost pumps

Figure 1. Rocket engine feed system historical development, designed by KBKhA

RD-0110 LOX-kerosene engines powered the third stage of the “Soyuz” booster, which put into orbit the cargo spaceships “Progress” and crew transport vehicles, including the international ships crew. Development of the RD-0110 engine was performed in 1963 in 9 months, with the first flight testing – in 1964. Since then this engine has been tested 1350 times with total burn time over 336500 sec. The external view of this engine is presented in the Fig. 2.

The RD-0124 LOX-kerosene engine was developed by KBKhA to replace the RD-0110 engine, and it has better performance. The energy performance was improved by converting to a closed cycle schematic. Due to this cycle the specific impulse of the RD-0124 engine was increased by 33 seconds as comparing to the RD-0110 engine. This allowed an increase of the payload mass of the launch vehicle by 950 kg. RD-0124 LOX-kerosene engine is meant for use in the “Soyuz 2” and “Angara”[1] boosters. The engine was designed in 1994 – 1995. The external view of the RD-0124 engine is presented in the Fig. 3.

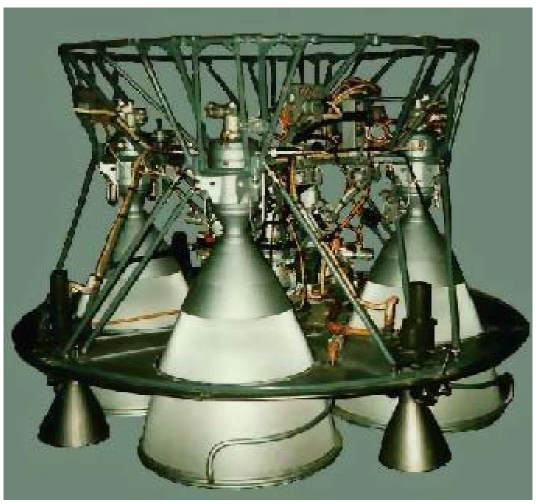

Figure 2. External view of the RD-0110 engine.

Figure 3. External view of the RD-0124 engine.

Table 1

Parameter	Parameter value	
	RD-0110	RD-0124
Engine thrust, kN	298.03	294.3
Specific impulse, sec	326	359
Chamber pressure, MPa	6.8	15.53

The main parameters of RD-0110 and RD-0124 engines are presented in Table 1. The RD-0124 engine specific impulse increase by 33 sec due to an increase in chamber pressure by 2.3 times resulting in the staged combustion engines higher performance compared to the gas generator engines.

These engines are four-chamber engines, i.e. four engine chambers are fed by one turbopump. The engines differ from each other in the engine cycle. The RD-0110 engine is a gas generator engine and RD-0124 engine is a staged combustion engine. The RD-0124 engine also has a more complex feed system including main turbopump, kerosene and LOX boost pumps.

III. RD-0110 and RD-0124 Engines Feed System Schemes

To provide acceptable suction performance the RD-0110 engine pumps have a double-inlet design with back-to-back centrifugal impellers, which allow the turbopump to operate at relatively low inlet pressures without using additional boost pumps. To provide high performances of RD-0124 engine main pumps and turbine, the turbopump rotor is a high-speed rotor. To provide inlet pressures of RD-0124 engine equal to inlet pressures of RD-0110 engine we need to use boost pumps for oxidizer and fuel lines. Feed system schematics for both RD-0110 and RD-0124 engines are shown in Fig. 4[2] and Fig. 5[2].

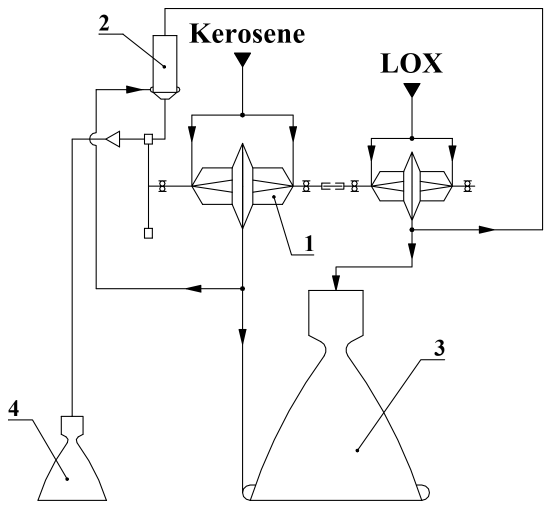

Figure 4. RD-0110 feed system scheme
1 – turbopump; 2 – gas generator; 3 – main chamber (4 chambers); 4 – control chamber (4 chambers).

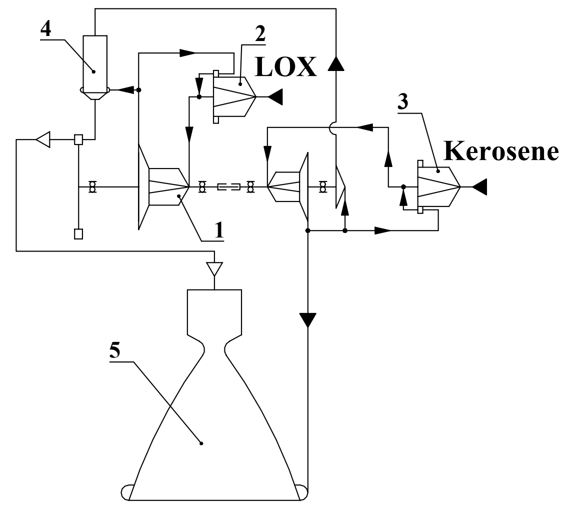

Figure 5. RD-0124 feed system scheme.
1 – turbopump; 2 – LOX boost pump; 3 – kerosene boost pump; 4 – gas generator (preburner); 5 – combustion chamber (4 chambers).

Turbo-axial boost pumps are used as boost pumps in the RD-0124 engine. The units include only one rotating part consisting of connected axial pumps wheels (inducers) and hydraulic turbine, that are brazed or welded onto the pump wheel external diameter. Due to the design simplicity the turbo-axial boost pumps are very reliable. These types of boost pumps are widely used in rocket engines developed by KBKhA.

IV. Turbopump Operability Parameters Comparison

The turbopumps are critical components during development of the rocket engine, since the turbopumps require a long time during design, manufacturing and engine certification. Complicated design, high rotor speed, the interaction between apparently independent turbopump and other components greatly affects each other's operating requirements are the reason that the turbopump failures may achieve to 50–70 percents of all engine failures during development tests. The difficulty of turbopump failures prevention during engine development is due to the fact that the turbopumps operate extremely fast. For example, turbopump rotor makes 500–1000 rotations per one second, and duration of failure process such as the design ignition and firing is a few hundredth parts of second. Because of this, development of high performance turbopumps for rocket engines is a complicated technical task[3].

At present the major differences in operational conditions between staged combustion and gas generator cycle for LOX-kerosene engines turbopumps are: substantially higher pressures in the pumps and turbines, and use of oxidizer-rich gas for drive the turbine. These differences create some features of development turbopumps for closed cycle engines. Special attention is paid to the following issues:

1) Provision of strength properties;
2) Provide required feed system suction performances;
3) Provide stable rotor dynamic performances;
4) Rotor thrust balancing;
5) Prevention of turbine parts inflammation in oxidizer-rich environment.

The comparison between the main parameters of the pumps and turbines of the RD-0110 and RD-0124 engines turbopumps is presented in Table 2.

Table 2

Parameter	Parameter Value	
	RD-0110	RD-0124
LOX pump		
Inlet pressure, MPa	0.28	
Discharge pressure, MPa	9.81	33.28
Pump flowrate, kg/s	64.5	65.46
Kerosene pump		
Inlet pressure, MPa	0.14	
Discharge pressure, MPa	14.32	36.56
Pump flowrate, kg/s	29.3	29.91
Turbine		
Inlet pressure, MPa	5.79	29.98
Discharge pressure, MPa	0.42	17.55
Turbine flowrate, kg/s	3.97	59.85
Turbine inlet temperature, K	1050	
Rotor rotation speed, rpm	18400	39000

The increase of the RD-0124 engine chamber pressure by 2.3 times, as compared to the RD-0110 engine chamber pressure, required an increasing in the LOX pump discharge pressure by 3.4 times. Moreover, turbines in staged combustion cycle operate at much higher pressures then those in open cycle engines such as gas generators.

The application of the staged combustion cycle in the RD-0124 engine has enabled increased pressure at the pump discharge, and also to total stress in the turbopump element. To compare the stress level of the RD-0110 and RD-0124 engines turbopumps, an analysis of the turbopump operability parameters was conducted based on following parameters:

1) Pumps discharge pressure,
2) Circumferential velocity at the tip diameters of the pump impellers,
3) Specific speed of the bearings,
4) Turbine inlet pressure,
5) Circumferential velocity at the turbine wheel mean diameter,
6) Turbine blade stress caused by centrifugal forces,
7) Turbopump weight and total weight of the feed system – weight of turbopump (TPA) and boost pumps (BTPA).

The comparison between the relative operability parameters of the RD-0110 and RD-0124 engines turbopumps (the relation between RD-0124 parameter and the RD-0110 similar parameters) is presented in Fig. 6. The numbers of the operability parameters correspond with the numbers presented in the list above.

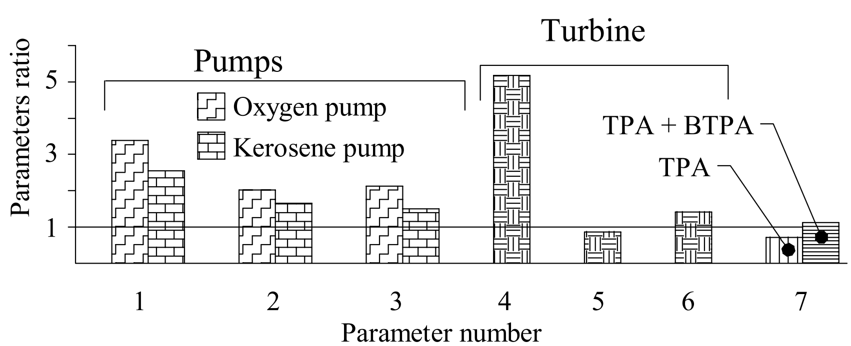

Figure6. Comparison of turbopump operability parameters.

Fig. 6 shows that all the RD-0124 engine turbopump values are higher than those of the RD-0110 engine turbopump with except of circumferential velocity at the turbine wheel mean diameter. The RD-0124 engine turbopump rotor speed is 2.1 times higher than the RD-0110 engine turbopump rotor speed. Hence, for staged combustion cycle engines turbopumps, a more detail sophisticated analysis is required not only for design strength but also to rotor dynamic parameters. RD-0124 engine turbopump has higher power and lesser weight than RD-0110 engine turbopump. However, the weight of the RD-0124 engine feed system is approximately 10 percents heavier than that of RD-0110 engine due to the boost pumps.

Dimensions of RD-0124 engine turbopump are significantly less than that of RD-0110 engine (Fig. 7).

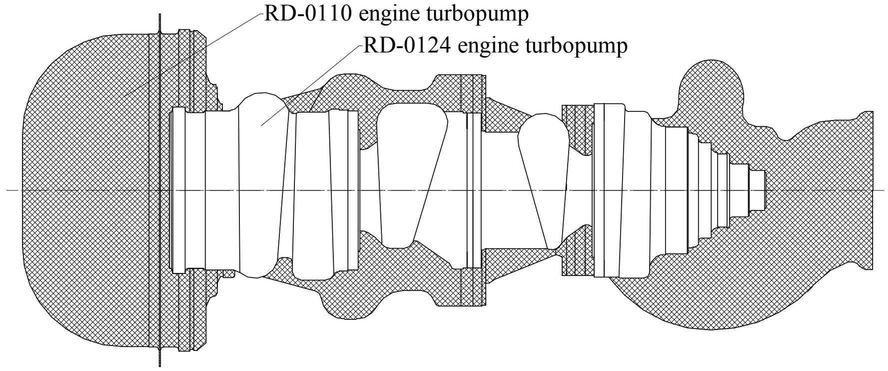

Figure 7. Comparison of RD-0110 and RD-0124 engines turbopumps dimensions.

V. RD-0110 and RD-0124 Engines Turbopumps Design Schemes and Features

The RD-0110 engine was developed in a period when KBKhA just had begun to develop rocket engines. In this period, many versions of turbopumps were evaluated. The RD-0110 engine turbopump[2, 4] was developed towards the end of this period. This turbopump (Fig. 8) is a single shaft integrated kerosene pump, LOX pump ant turbine. The use of double-inlet design with back-to-back centrifugal impellers with inducers assures good suction performance. The supersonic turbine is driven by fuel-rich generator gas. The pumps housings, impellers and inducers are made from aluminum alloys. Shrouded impellers have milled blades and brazed shrouds. Bronze floating rings are used as impeller seals. Integrally bladed disk turbine wheel are manufactured by precision casting from nickel alloy. The turbine housing is a welded design. Pumps rotors are sub-critical i.e. they operate at speed lower than first critical speed. The rotor supports propellant cooled ball bearings. Both rotors are axially thrust balanced without special thrust balance devices due to low pressure in the turbine cavity and use of double-inlet pump designs.

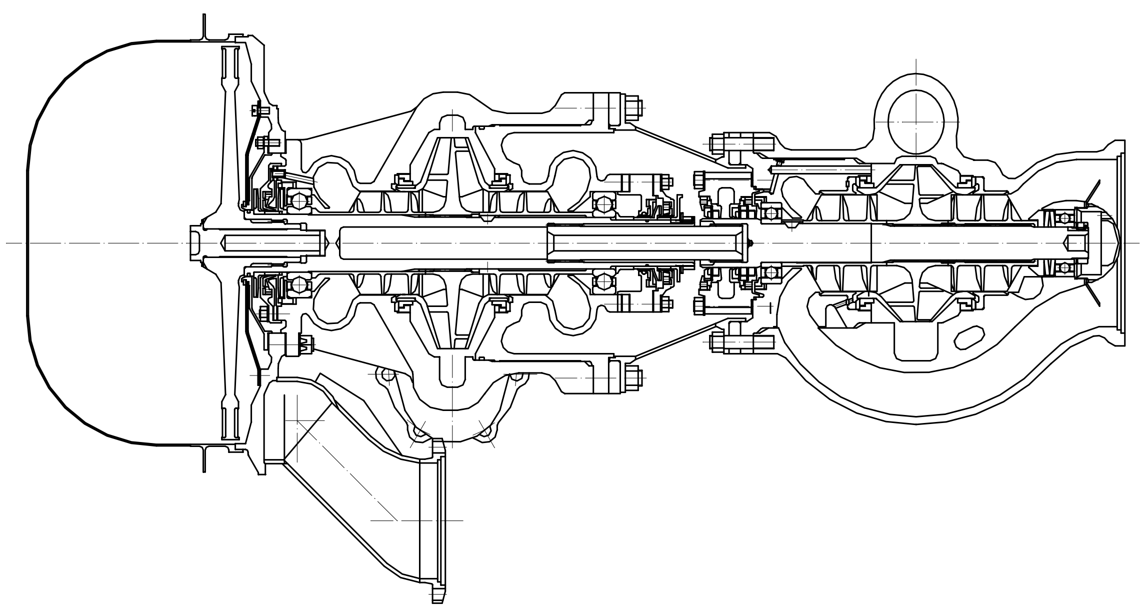

Figure 8. RD-0110 engine turbopump design scheme.

KBKhA has developed turbopumps design concept for staged combustion cycle engines based on their own experience. This concept was used during development of RD-0124 engine turbopump. The main features of this concept are[3]:

1) Minimum parts and simple design,
2) Minimum welding joints,
3) Minimum external flange joints,
4) Extensive using of cast parts,
5) HIP processing for cast parts,
6) Application a powder metallurgy for manufacturing of high-loaded parts,
7) Application of vane-less gas distributor for the turbines which are driven by oxidizer-rich generator gas,
8) Use of floating ring seals in the pumps,
9) Axial thrust balance of the rotor by use of a thrust balance system combined with the impeller main disc[5],
10) Rotor high speed testing at the full rotor operating range.

The RD-0124[4] engine turbopump design scheme is presented in Fig. 9. Design differences of RD-0124 engine turbopump from RD-0110 engine turbopump are:

1) Axial balance of each rotor by tthrust balance system combined with each impeller main disc[5],
2) Pumps housings and impellers are castings made from stainless steel and the turbine housing is a casting made from nickel alloy,
3) Blisk type turbine wheel is manufactured from high strength nickel alloy by powder metallurgy; blades are electrical discharge machined,
4) Sets of traditional Russian design procedures that improve hardware oxidation tolerance were used in RD-0124 engine turbopump[6]. Possible causes of LOX pump and turbine combustion are: peak transient temperature, friction and fretting, foreign metal particles. Additionally, the turbine has a vane-less gas inlet to the turbine. The latter, now it is typical design for KBKhA turbines driven by oxidizer-rich generator gas.

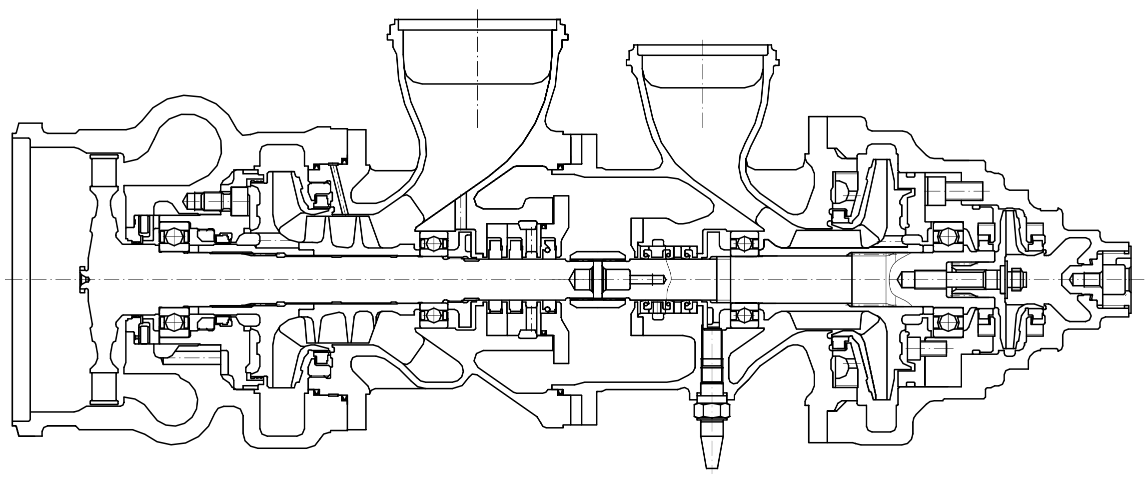

Figure 9. RD-0124 engine turbopump design scheme.

VI. Turbopumps Development Tests Peculiarities

Development tests of gas generator cycle engine turbopumps are usually conducted independently under conditions close to their operation modes. Independence of the gas generator turbopump operation to the other units and engine operation at relatively low pumps discharge pressures and turbine outlet pressure close to ambient pressure facilitates testing of the component level turbopump at engine conditions. In staged combustion cycle engines, the interaction between components greatly affects each other's operating requirements. This is especially true during start and shutdown transient modes. Because of this, the requirements to develop staged combustion cycle engines', operating at elevated discharge pressures has significantly complicated turbopump component development tests. For staged combustion engines turbomachinery, autonomous tests are prohibitively expensive, extend the development time, and do not accurately simulate the conditions that will be experienced during engine operation. Even turbopump component tests with positive results do not exclude the possibilities of engine failures on development tests. This makes component testing for staged combustion engines less beneficial.

The methodology developed determines reliability, schedule and costs of turbopump and engine development. KBKhA developed the method of turbopump development[3] based on their staged combustion cycle engines turbopumps experience.

KBKhA employs a method of sub-component development that specifies separate tests of basic structural components over a wide range of operating conditions. The main advantages of such tests are:

1) Wide opportunities for turbopumps design element study,
2) Parallel development tests of turbopump and other engine units reduce of the engine development time,
3) Investigation of the operation limits of structural components,
4) Discover ways of improving the design for development of turbopumps for next-generation engines.

Sub-component development of turbopumps is carried out on substitute hardware and divided into two phases. Testing under first phase is done prior to engine level tests to validate the strength and safety margins of each of the design elements, and to empirically verify and update the performance characteristics of the pumps, turbines, thrust balance devices, and rotor dynamic characteristics. The objective of this phase is to prepare for the start of the engine development tests at initial operating modes for limited duration. The sub-component development tests reduce the term of the engine development.

The second phase of the sub-component level testing is a detailed examination of design elements in order to ensure the statement of work requirements were met and to ensure the detection and elimination of potential flaws and shortcomings in the design during all engine operation modes and discover ways of improving the turbopumps design. The second phase content depends on the statement of work requirements and previous experience in design of similar turbopumps. The numerical analysis in some cases allows replacing the experiments with computer simulations that are especially effective at turbopump design study with availability of multi-variant solutions. The scope and distribution of work between the phases is based on the complexity and level of innovation being incorporated. When the minor modifications to a previously developed design are being evaluated, the testing required in both phases may be minimized. Similarly, when little previous experience has been established, the first phase must be approached in comprehensive manner to minimize risks during subsequent testing.

In some cases it is possible to perform the turbopump preliminary development testing in the power head. The power head is a simplified engine without a chamber and with fewer control valves, and with some measures to improve maintainability. During turbopump testing of a power head the same tasks are performed as during sub-component testing. An obvious advantage of such testing is possibility to conduct a preliminary check of turbopump performance at start, throttling and shutdown modes. Such testing is expedient if there is a higher risk of failures due to the new design solutions and test tasks introduced.

During engine level turbopump tests, the turbopump parameters are updated and its performance is verified at all engine operation modes including start and shutdown transients.

Such method of turbopump development tests requires minimum use of hardware and provides the least number of engine level turbopump tests.

VII. Peculiarities of Materials and Manufacturing Methods for Gas Generator and Staged Combustion Cycle Engines Turbopumps

Differences in materials and manufacturing methods are required for gas generator and staged combustion cycle engines pumps and turbines configuration. Taking into account higher power and staged combustion cycle engines pumps and turbines experience, materials with higher mechanical properties have to be used for their manufacturing. Aluminum alloys have been widely used to manufacture the gas generator cycle engine pumps, while steels have been used to manufacture staged combustion cycle pumps. High-strength nickel alloys are used for manufacturing the staged combustion cycle turbines. For staged combustion cycle turbopumps the following manufacturing methods are widely used: nickel and steel precision casting, HIP processing for cast parts, powder metallurgy. High-frequency tests at operational rotation speed are used to check the turbopumps rotors dynamical characteristics. These tests provide a combined method of rotors manufacturing quality verification.

KBKhA has extensive experience in powder metallurgy and hot isostatic treatment applications, such as:

1) Hot isostatic treatment of cast parts,
2) HIP diffusion bonding of various kinds of materials,
3) Manufacturing of nuts and bolts blanks by powder metallurgy,
4) Manufacturing of impellers, turbine wheels, guide vanes and nozzle blocks blanks from nickel and titanium alloys by powder metallurgy with flow path formation during subsequent operations,

5) Manufacturing of impellers, turbine wheels, crossovers and nozzle blocks by powder metallurgy using nickel and titanium alloys with flow path formation by powder metallurgy during HIP process.

VIII. Conclusion

Staged combustion cycle liquid-propellant rocket engines turbopumps compared to gas generator cycle engines turbopumps have more evaluated power and stresses that requires careful turbopump design and meticulous development. Unlike the gas generator cycle engines turbopumps, the staged combustion cycle turbopumps require innovations, application higher strength materials, new manufacturing techniques and new methods of experimental development.

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