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Ground Test Demonstrator Engine Boost Turbopumps Design and Development

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Boost turbopumps for a ground test demonstrator engine developed by Pratt & Whitney have been built by Konstruktorskoe Buro Khimavtomatiyi (KBKhA) in cooperation with Pratt & Whitney. The paper discusses design approach, development results and design simplicity of the liquid hydrogen (fuel) and liquid oxygen (oxidizer) boost turbopumps (FBTP and OBTP). The paper describes element-wise experimental development principles used for the boost turbopumps which are based on component sub-assembly level testing in simulated conditions and fluids thus assuring low cost development and excluding the necessity to conduct all the tests with the real propellants. The OBTP and FBTP experimental characteristics are presented in this paper including comparison of the OBTP performance characteristics in water and in liquid oxygen and the FBTP rotor dynamics characteristics throughout the range of operating speeds. Element-wise development allows not only assuring fulfillment of design requirements but also to determine operability margins of the elements and identify the ways for possible design improvements.

Introduction

Several companies leading the world in liquid rocket propulsion participated with Pratt & Whitney in the development of an oxygen-hydrogen expander cycle ground test demonstrator engine. KBKhA took part in this international cooperation as a developer of the hydrogen and oxygen boost turbopumps as well as the main oxygen turbopump.

Boost turbopumps allow the engine to start and operate at minimum engine inlet pressures, permitting the use of unpressurized cryogenic propellant tank systems to optimize weight and performance.

KBKhA possesses extensive experience in the design of boost turbopumps. The first boost turbopump designed at KBKhA was for the nuclear rocket engine RD-0410 hydrogen supply system. Its development was started in 1965. Since 1977 KBKhA has designed boost turbopumps for liquid rocket engines. Seventeen boost turbopumps have been designed for different engines including the oxygen-hydrogen RD-0120 sustainer for Energiya launcher, the oxygen-hydrogen RD-0146 upper stage engine for Proton and Angara launchers, and the oxygen-kerosene upper stage engine for the Soyuz-2 launcher[1].

This experience enables the development of turbopumps on an accelerated schedule with assured performance characteristics[2]. This is done through application of KBKhA's experimental design techniques, which specify testing at the component subassembly level to verify that required turbopump parameters have been attained or surpassed. KBKhA and Pratt & Whitney used this experimental design verification technique in collaboration during the boost turbopumps and main oxygen turbopump development. The work starts with analysis of design options based on prior experience, detailed analysis of the designs and finally experimental verification of the design solutions and technical characteristics.

PROGRAM REALIZATION
UNITED CONCEPTS OF THE COMPANIES

The demonstrator engine (figure 1) differs from its predecessor RL10 by having two main turbopumps instead of one and two boost turbopumps.

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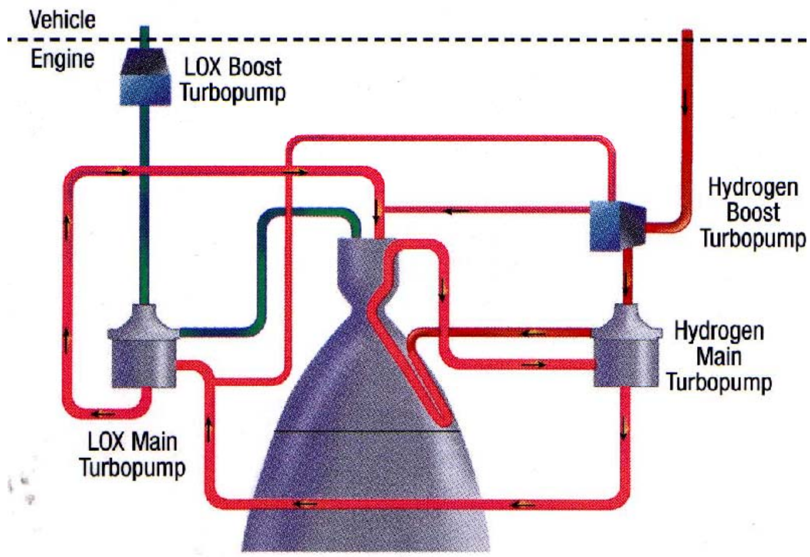


Figure 1. Ground Test Demonstrator Engine

The demonstrator engine has twice the thrust of the RL10 with no increase in size and is a logical continuation of development to provide improved expander cycle engines. The design activities at KBKhA for the RD-0146 engine contributed significantly to the basis of development of the turbomachinery for the Pratt & Whitney demonstrator. The 22K lbf RD-0146 oxygen-hydrogen engine is the first Russian expander cycle engine design. This engine is one of the new generation expander cycle engines, and like the Pratt & Whitney demonstrator uses four turbopumps—two main and two boost turbopumps (figure 2). Boost pumps make the engine operable at an engine inlet hydrogen pressure equal to the saturated vapor pressure and an oxygen pressure very near the saturated vapor pressure. The main hydrogen turbopump rotates at a speed higher than the speed of any turbopump previously developed in the world.

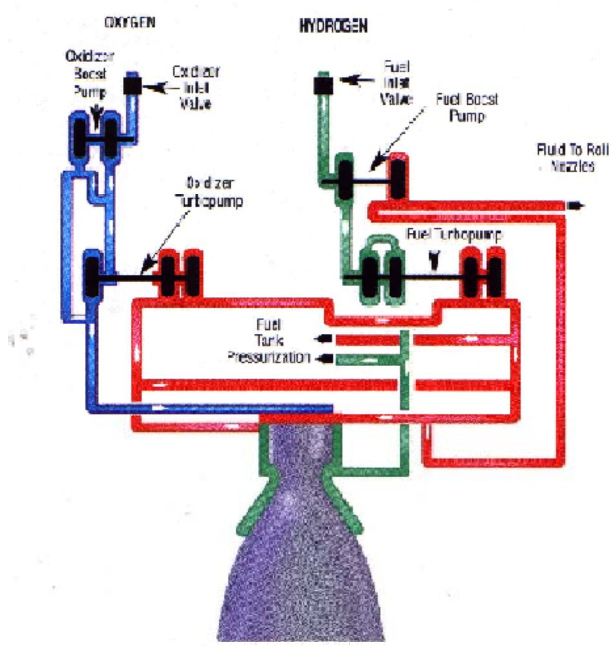
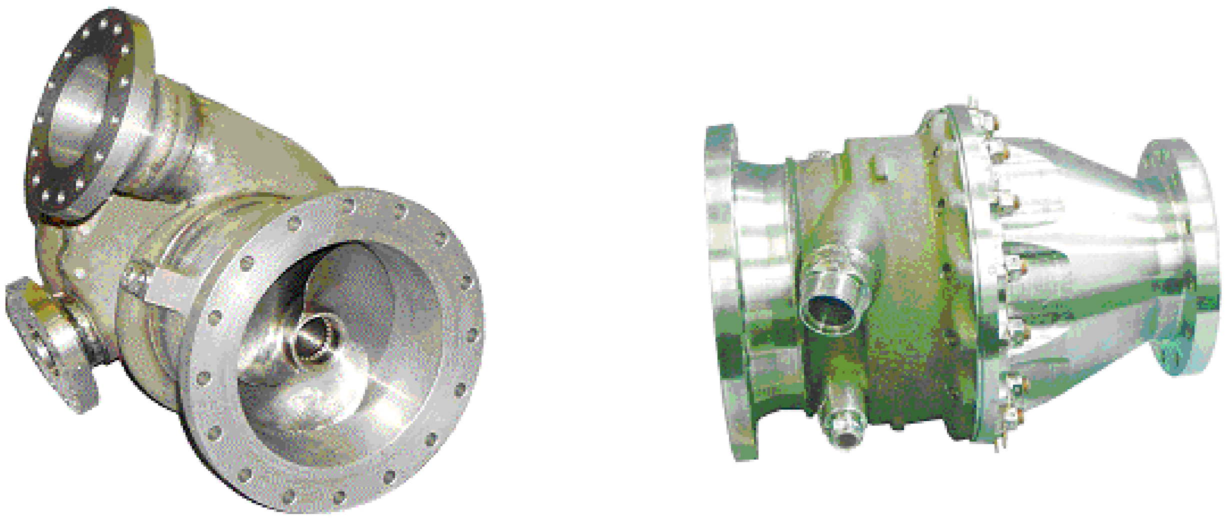


Figure 2. RD-0146 Engine

The development of the hydrogen and oxygen boost turbopumps for the demonstrator engine (figure 3) was performed based on Pratt & Whitney design requirements for functional and physical interfaces.



a b

Figure 3. Hydrogen (a) and Oxygen (b) Boost Turbopumps

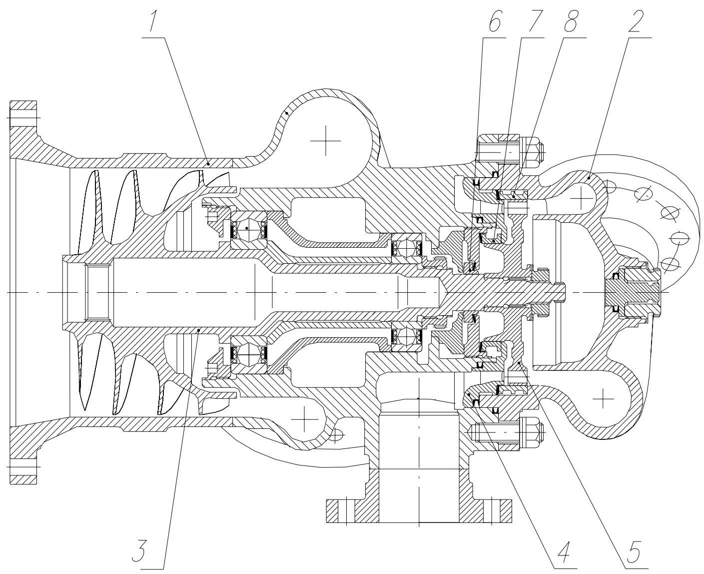
The cost of turbopump development was held down by the application of previously evolved engineering solutions and technologies thus minimizing the costs of the design, production and test infrastructures readiness and verification testing. The low manufacturing cost was aided by KBKhA's rich practical experience in adapting turbopump designs to production capabilities as well as extensive use of cast casings, standardized structural elements; minimal number of parts and joints (bolted, welded and brazed), routine test procedures based on established practices.

The development of the boost turbopumps for Pratt & Whitney was founded on experience developing turbomachinery for the RD-0120, RD-0124, RD-0146 engines. The FBTP and OBTP full cycle of development, from the receipt of technical specifications up to delivery of the turbopumps to Pratt & Whitney, was accomplished in about 2 years. The program was divided into phases during which Pratt & Whitney coordinated design efforts controlling the scope of work and schedule requirements fulfillment. Completion of important work phases culminated in the release of engineering reports. After each report had been released, it was reviewed with the participation of Pratt & Whitney and KBKhA specialists. Such reviews enabled report corrections and clarifications related to differences in design, manufacturing, and testing standards used in the two companies. Based on the presented data Pratt & Whitney performed the system level analysis required to integrate the turbomachinery into the comprehensive engine system.

BOOST TURBOPUMPS DESIGN FEATURES

Hydrogen boost turbopump

The hydrogen boost turbopump consists of an axial-diagonal flow pump and a single stage axial flow gas turbine (figure 4). A flow separating system is placed between the pump and the turbine. Floating ring clearance seals separate the turbine and the pump interiors. The floating ring clearance seals are widely used by KBKhA in turbopump designs. The floating rings are pressed to the housings with axial springs [3].

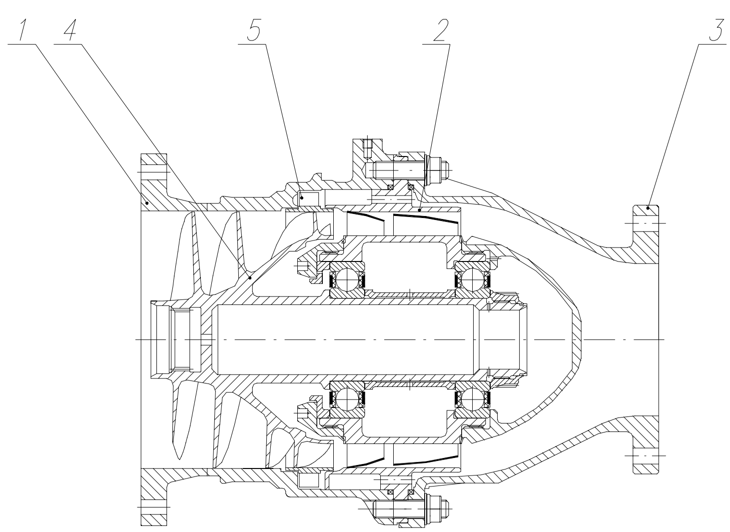


1 – pump housing; 2 - turbine exhaust volute; 3 –shaft with inducer; 4 – nozzle block; 5 – turbine wheel; 6, 7, 8 – floating rings.

Figure 4. Hydrogen boost turbopump

Oxygen boost turbopump

The oxygen boost turbopump has traditional KBKhA design (figure 5). The axial hydraulic turbine consists of a turbine wheel and two supply nozzles. The turbine wheel is comprised of a blade row attached to the inducer blade tips at the pump outlet section. The inducer, the shaft and the turbine wheel are incorporated into a single assembly unit. As a result the oxygen boost turbopump has simple design and high reliability since the rotor has only one rotating part.



1 – inlet housing; 2 - flow straightener; 3 -discharge housing; 4 – shaft with inducer; 5 –turbine wheel.

Figure 5. Oxygen boost turbopump

PRINCIPLES OF ELEMENT WISE EXPERIMENTAL DEVELOPMENT

The turbopump subassembly level testing performed at KBKhA increases the certainty of endowing each design element with the requisite functional characteristics under the turbopump operating conditions, and also allows the designer to define performance variations for each element before incorporating the assembly into an engine for an integrated system test. Another important advantage of testing at the subassembly level is the ability to determine operating margins and identify needed improvements that should be made before the final manufactured assemblies are installed into the engine system as well as for identification of subsequent system improvements.

The element wise development of the turbopumps includes the following types of testing:

- pressure testing of casings;
- strength testing of rotor parts by spinning;
- comprehensive rotor dynamics tests over the range of operating speeds;
- pump performance characterization over the entire range operating conditions, including startup and shutdown;
- pump performance characterization at negative flows;
- pump cavitation characteristics tests over a wide range of flow rates;
- turbine performance characterization over a wide range of engine operating conditions, including startup and shutdown;
- verification of fuel boost pump performance in hydrogen;
- verification of oxidizer boost turbopump performance in oxygen.
- Since it is not possible to cover all of the tests in the frame of a single paper only some of them are discussed hereunder.

HYDROGEN BOOST TURBOPUMP PERFORMANCE CHARACTERISTICS

The hydrogen boost pump hydraulic tests were conducted in water with simulation of the pump operating conditions based on affinity laws at Q/n=idem. The rotor speed for the tests was selected in order to simulate the pump structural loads meaning that the pump developed pressure should be equal to the FBTP pressure rise at the engine rated thrust level. The pump flow rate was measured by a flow meter and controlled by a throttle downstream of the pump. The rotor was driven by an electric motor with toque measurement capability. Figure 6 presents the pump head rise and efficiency characteristics, experimentally defined throughout a wide range of flows. The head rise curve extends into the second quadrant at negative flows. The negative flows were achieved by overdriving the pump outlet pressure with higher pressure supplied from the test bench system. The head rise characteristic curve is normalized in relation to the head rise parameter H/n2 obtained at nominal flow rate parameter $Q/n_{nominal}$.

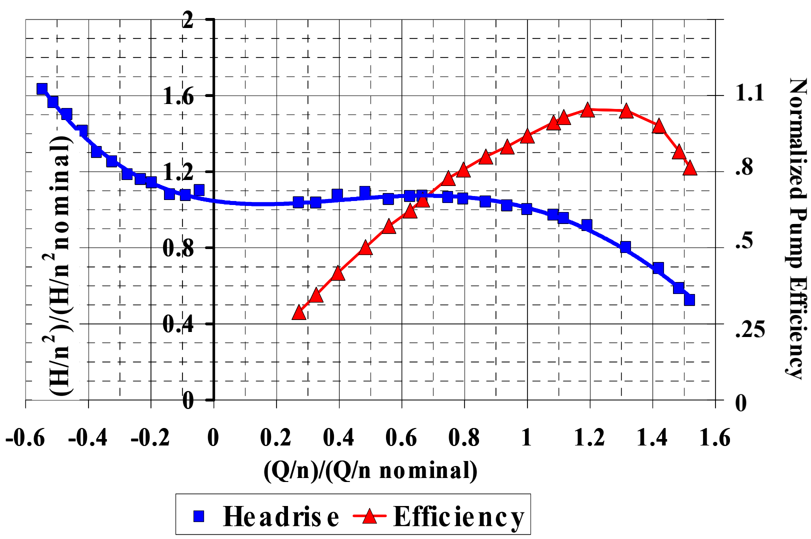


Figure 6. Fuel boost pump head rise and efficiency characteristics

Figure 7 presents the pump suction specific speed characteristics Nss based on cavitation test results. The pump has high suction specific speed while retaining high efficiency which is one of the main characteristics of the axial diagonal pump design featuring a profiled hub and high gradient of the tip-to-hub outlet blade angle growth.

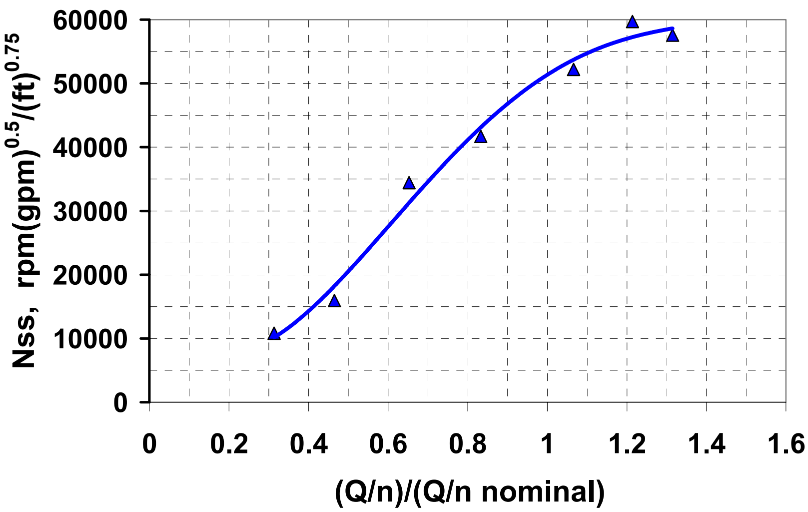


Figure 7. Fuel boost pump suction specific speed characteristics Nss

OXYGEN BOOST TURBOPUMP PERFORMANCE CHARACTERISTICS

The OBTP turbine was driven by high-pressure water supplied by the test facility pump. The rotor speed was selected to simulate the turbine structural loads meaning that the pressure drop through the turbine should be equal to the OBTP turbine pressure drop at the engine rated thrust level. Figure 8 presents the OBTP developed head and total efficiency characteristic curves, experimentally defined in water throughout a wide range of flows. The head rise curve extends into the second quadrant at negative flows. The negative flows were achieved by shutting off the outlet flow with the downstream throttle thus redirecting the flow from the turbine to the pump inlet. The water test head rise characteristic curve is normalized in relation to the head rise parameter H/n^2 obtained at nominal flow rate parameter Q/n_{nominal}. The turbopump total efficiency is defined as pump fluid horsepower divided by turbine available energy.

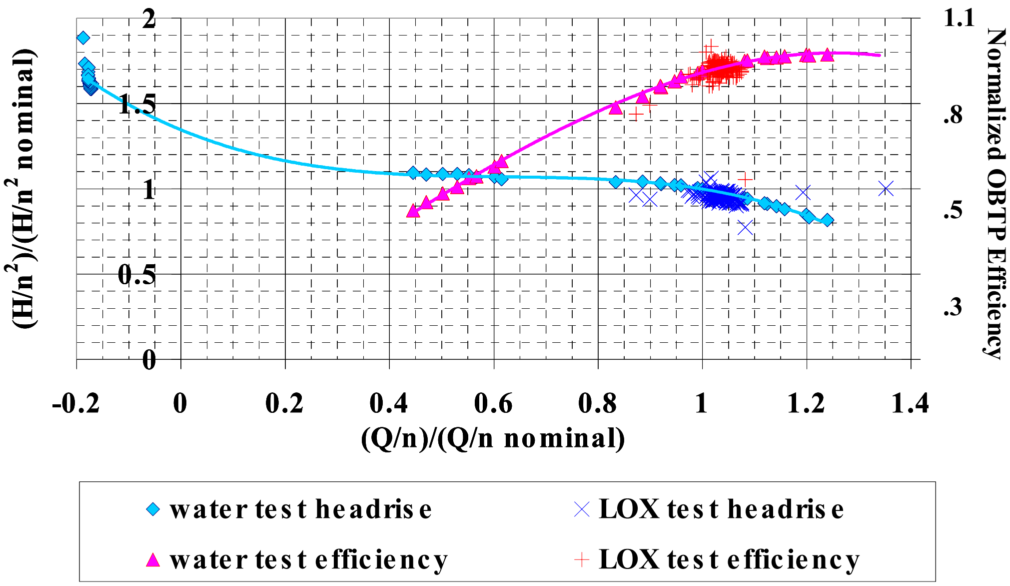


Figure 8. Oxidizer boost pump head rise and total efficiency characteristics

In order to verify the OBTP operability it was tested in liquid oxygen operating in the conditions close to nominal at the engine rated thrust level operation. The oxygen test results are also presented in figure 8 for comparison. The oxygen test data is normalized against the nominal head rise parameter H/n^2 defined at water tests at $Q/n_{nominal}$. The comparison reveals good matching between the water test characteristics and oxygen test data. Small discrepancies are due to the measurement tolerance and oxygen density estimation errors.

HYDROGEN BOOST TURBOPUMP ROTOR HIGH SPEED TESTS

Balancing of the main turbopump rotor is an important procedure to assure turbopump operability. KBKhA design practices include rotor high speed tests conducted over the range of operating speeds after rotor reassembly[4]. These tests are effective to verify the quality of the rotor components and rotor assembly procedure. The hydrogen boost turbopump operates at high speeds close to the speeds typical for the main turbopumps operation. Thus the main turbopump balancing technique was adopted for the FBTP rotor.

The FBTP rotor balancing included:

- low speed balancing of the shaft with inducer;
- low speed balancing of the turbine wheel;
- low speed balancing of the assembled rotor;
- rotor high speed tests over the entire range of operating speeds.

Structural tests preceding the rotor balancing were conducted by spinning separately the rotor shaft with inducer and turbine wheel to the speeds exceeding the maximum operating speed. This procedure stabilizes rotating parts size in order to improve the assembly balancing accuracy. Rotor high speed tests were conducted in a special installation (Figure 9).[5]

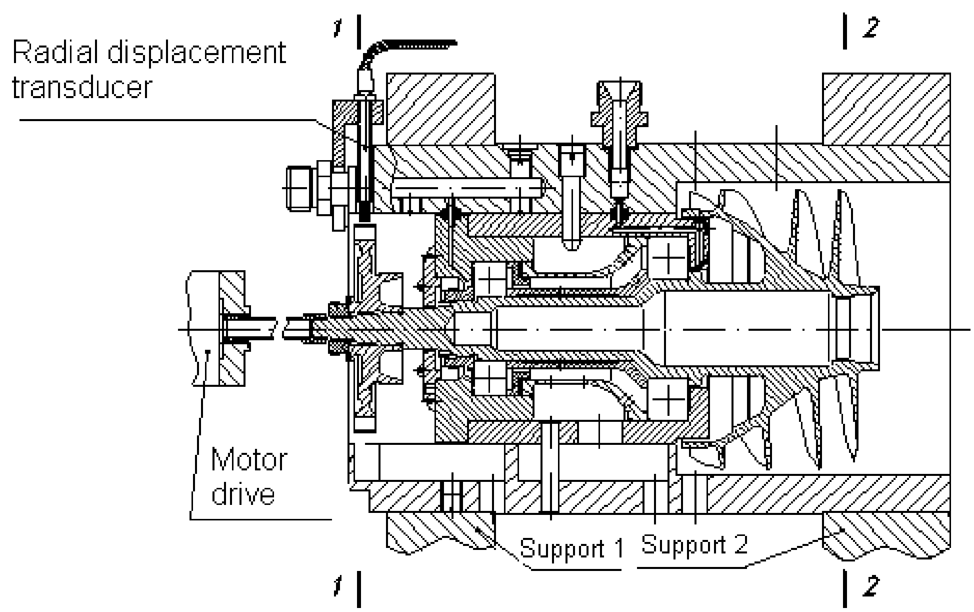
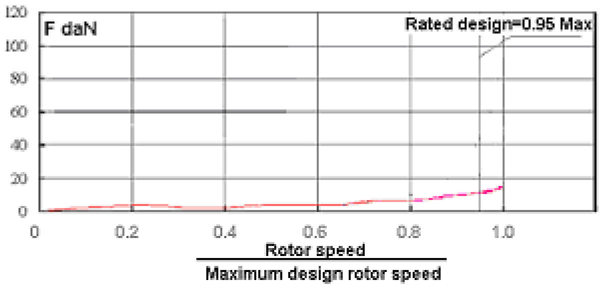


Figure 9. Rotor high-speed test installation

Support loads and radial displacement at the turbine wheel outer diameter were measured during the tests. During the rotor manufacturing processes development high-speed tests are conducted in order to determine the influence of the design and manufacturing factors on the rotor dynamics characteristics. The FBTP rotor high-speed test results are presented in figure 10. The curves show that the support loads did not exceed 20 daN and the radial displacement was no larger than 30 micron.



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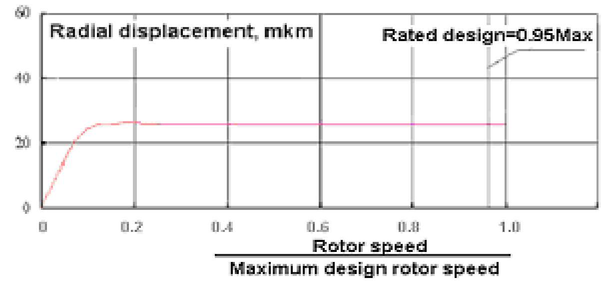

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Figure 10. Rotor support loading a) and radial displacement b)

SUMMARY

The full cycle of the boost turbopumps design, manufacture and experimental development for the demonstrator engine was accomplished in about 2 years. The presented incremental approach and examples of component sub-assembly level testing used for the engine boost turbopumps assured cost effective and low risk development. The incremental development technique allows not only achieving high parameters but also to determine the component operability margins and reveal possible design improvement. The test results revealed that the turbopumps met or exceeded design requirements, verified their operability and justified the used development approach.

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