Proposals for Improving the Efficiency and Durability of the Turbines of Turbo-Pump Assemblies in Liquid-Propellant Rocket Engines by Using Double-Sided Crest-Type Radial Labyrinth Seals

V S Vasiliev, P S Levochkin, V K Chvanov and S F Timushev

1 NPO Energomash named after academician V.P. Glushko, 1 Burdenko street, Khimki, Moscow Region, 141400, Russia.
2 Moscow Aviation Institute (National Research University), 4 Volokolamske shosse, Moscow, 125993, Russia.
3 Post-graduate student, NPO Energomash named after academician V.P. Glushko, 1 Burdenko street, Khimki, Moscow Region, 141400, Russia.

Abstract. Nowadays the improvement of the design of liquid-propellant rocket engines (LPREs) depends on a whole range of factors and activities, among which it is possible to distinguish, for example, the improvement of energy characteristics that are part of the LPREs, units and assemblies. The article compares the operation of an LPRE turbo-pump turbine using double-sided and single-sided labyrinth seals in Energomash's engines. Main geometrical parameters of each seal variant, images built for the calculations of 3D models of seals, the resulting calculation grid, as well as graphs of the pressure distribution and velocity fields are presented for a visual comparison. Sectoral leakage was calculated for each variant of the seal, a calculated assessment of the possibility of reducing the temperature of the working gas at the turbine inlet is carried out. In the future attention should be paid to a more detailed study of this type of seals using of modern computing power.

1. Introduction
Greater fuel efficiency is the key objective of activities to improve the design of liquid-propellant rocket engines (LPREs). It is achieved by enhancing the fuel efficiency of engine units and assemblies. Ancillary tasks include extending the service life, reliability and re-usability of units and assemblies, and reducing the time required for their design and manufacture. In order to succeed in all of these tasks, designers should address a range of issues at all stages in the creation of LPREs, from R&D to serial production [1, 2].

Optimal design of the turbo-pump units (TPUs) of LPREs is among the most important of these issues [3, 4]. Various approaches to modelling and analysis are used in TPU design. The present article focuses on the design of the radial labyrinth seals of TPU turbines and aims to give a conclusive assessment of how the geometry of the shroud turbine seal impacts the flow of working gas through the channels of the seal by numerical modelling of three-dimensional flow.

TPU turbines on LPREs designed by Energomash, with afterburning of the oxidizing generator gas, have fairly large gaps in the radial labyrinth seals, allowing substantial leakage of gas through the flow...
sections of the seals, which in turn has an impact on the operation of the turbine. The proposal is to reduce leakage by altering the design of the radial labyrinth seals. At present, single-sided crest-type radial labyrinth seals are widely used on the TPU turbines of Energomash LPREs. However, the use of double-sided seals could reduce leakage and increase the efficiency of the turbine. The use of double-sided seals has already been proposed in various engine designs, but the proposals have not been implemented in contemporary engines [5]. Figure 1 shows the visual form of the seals.

![Figure 1](image_url)

**Figure 1.** A single-sided (a) and double-sided (b) crest-type radial shroud labyrinth seal.

2. **Description of the approach**

The present article compares the performance of a single-sided crest-type radial shroud labyrinth seal (currently used in the turbines of the TPU of Energomash LPREs) with double-sided alternatives by numerical simulation of the three-dimensional flow in a stationary formulation.

Calculations are carried out for shroud seals with various geometries in order to identify the design, which ensures minimum leakage rate and, as a consequence, highest efficiency of the turbine. Therefore, the main evaluation criterion is the compaction leakage rate ("ṁ"). The reliability of modern LPREs, particularly those intended for multiple use, depends to a large extent on reliable operation of the TPU turbine, which is largely determined by the temperature of the working gas [6]. It is therefore important to find ways of reducing the gas temperature without power losses, and the present article also offers estimates of success in achieving this objective [7].

3D models of alternative designs for the flow sections of the seals were obtained using a CAD system. Since the problem is symmetrical to the axis of rotation, any sector can be used for calculation, such as for instance a 15-degree sector, which significantly reduces the calculation time in comparison with a full 3D model of the flow section. The geometry of the flow section is designed taking account of the main features of the working gas flow in the shroud seal channels, determining a specific leakage rate for a given effective pressure differential. The geometric parameters of the 3D models also take account of the so-called "umbrella effect", caused by low-temperature oxygen flows from the bearing support, which cool the surface of the turbine impeller, causing it to bend. As a result, the
impeller blades move towards the blades of the nozzle apparatus. The Figure 2 below shows how the impeller bends during engine operation (the geometry scale is in millimeters).

![Figure 2. The umbrella effect in the 3D-model.](image)

Calculations for the 3D models were carried out using a computational hydrodynamics program [8]. The grid is built automatically, with adaptation to the specified geometry, and the average grid size in each model is above 550,000 cells. An initial grid with parallelepiped cells is defined in the calculation area, and then geometrical sub-regions are selected for calculation using a denser grid. Each cell of the initial grid is divided in these sub-regions into 8 equal cells of a new adaptation level. If necessary, the cells are divided again, and the operation is repeated until the required level of accuracy is obtained. This sub-grid resolution of geometry approximates curvilinear boundaries on a rectangular grid. The cells through which the boundary passes lose their original parallelepiped form and are transformed into arbitrarily-shaped polyhedrons. This approach enables a sufficient degree of accuracy in calculations even with a relatively low number of grid nodes.

The calculation is carried out using an iterative method from zero initial conditions. At the beginning of the calculation, for the period of pressure growth, the time step is $10^{-4}$ s, after which it is set automatically and amounts to approximately $10^{-8}$ s.

The values of the boundary parameters are provided by the operation of a particular Energomash LPRE and are as follows:

- temperature of the working gas at turbine inlet = 581.4 °C;
- temperature of the working gas at turbine outlet = 467.9 °C;
- absolute pressure at turbine inlet = 539.37 kgf/cm²;
- absolute pressure at the turbine outlet = 283.92 kgf/cm²;
- rotation speed of the turbine impeller = 22,825 rpm.

![Figure 3. Boundary surfaces in the calculated seal model.](image)

The boundary surfaces in the calculated seal model is shown in figure 3.
The calculation area consists of four sub-regions:
1 (blue) - working gas input surfaces (input parameters specified).
2 (green) - working gas output surfaces (output parameters specified).
3 (red) – turbine impeller surfaces (rotation condition specified).
4 (gray) - turbine stator surfaces (non-rotating wall).

The numerical modelling used mathematical models of computational gas dynamics that describe the motion of a working fluid at various speeds, taking account of the effects of compressibility, turbulence and heat transfer, and the k-ε model of turbulent flow for modelling of gas flow at large and small Reynolds numbers.

The calculation results were used to generate graphs of pressure distribution (figures 7, 12, 17 and 22) and velocity fields (figures 8, 13, 18 and 23), and sectoral leakage was calculated for each variant of the seal. Also, for each seal option, main geometrical parameters (figures 4, 9, 14 and 19), 3D-model (figures 5, 10, 15 and 20) and calculation grid (figures 6, 11, 16 and 21) are given.

3. Calculation results.
Variant No.1. Initial geometry. The principal criteria for the selection of this design are the use of a single-sided crest-type seal to reduce the contact area of the seal’s working surfaces, and the application of spiral design of the crest optimizing the downstream entrainment of microscopic particles.

The leakage value is $\dot{m} = 1.502062$ kg/sec.

![Figure 4. Main geometrical parameters of the seal.](image1)

![Figure 5. 3D-model of the seal.](image2)

![Figure 6. Calculation grid.](image3)
Variant No.2. A double-sided crest-type radial labyrinth seal, retaining main geometrical parameters of the original seal.

The leakage value is $\dot{m} = 1.622974 \text{ kg/sec}$.

**Figure 7.** Pressure distribution in the seal.

**Figure 8.** Velocity field in the seal.

**Figure 9.** Main geometrical parameters of the seal.
Variant No.3. A double-sided crest-type labyrinth seal, retaining the basic geometric parameters of the initial seal, but reducing the gap between the crests of the turbine impeller and the crests of the stator wall by increasing the height of the crests. Development testing of engines at Energomash has shown that it is feasible to manufacture seals with gaps as small as 0.15 mm.

The leakage value is $\dot{m} = 1.349547 \text{ kg/sec}$. 
**Figure 14.** Main geometrical parameters of the seal.

**Figure 15.** 3D-model of the seal.

**Figure 16.** Calculation grid.

**Figure 17.** Pressure distribution in the seal.
Figure 18. Velocity field in the seal.

Variant No.4. A double-sided crest-type labyrinth seal, retaining the basic geometric parameters of the initial seal, but reducing the gap between the crests of the turbine impeller and the crests of the stator wall by bringing the counterparts of the seal closer together. The leakage value is $\dot{m} = 1.235992$ kg/sec.

Figure 19. Main geometrical parameters of the seal.

Figure 20. 3D-model of the seal.

Figure 21. Calculation grid.
Figure 22. Pressure distribution in the seal.

Figure 23. Velocity field in the seal.

4. Conclusions
The present article reports the results of numerical modelling of gas-dynamic processes in the flow section of a shroud seal in the TPU turbine of a liquid-propellant rocket engine.

The values of sectoral leakage obtained for the seal variants in question are given in Table 1.

| Seal variant No. | Leakage, $\dot{m}$ (kg/sec) |
|------------------|-----------------------------|
| 1                | 1.502062                    |
| 2                | 1.622974                    |
| 3                | 1.349547                    |
| 4                | 1.235992                    |

As seen from the calculations, the best result in terms of reducing the flow rate of working gas in the shroud seal of the turbine, in comparison with the initial geometry, is offered by variant No. 4, which uses a double-sided crest-type radial seal with reduction of the radial clearance in the shroud seal, providing a reduction of the leakage rate.

Calculation of turbine efficiency variation due to the geometry of individual seal variants shows that a slight change in the temperature of the working gas is also obtained. By increasing the efficiency of the turbine, without changing the capacity, seal No.4 provides a decrease in the temperature of the working gas at turbine inlet by approximately 1.5-2% (8-12 °C). Lowering the temperature of generator gas entails greater reliability and efficiency of the TPU turbines of the LPRE.

Future research should focus on detailed studying of this type of seal, considering other possible changes in its geometry and conducting more detailed analysis of design parameters in order to determine the effect of geometric dimensions on the leakage value. Strength calculations should also
be carried out in order to establish how leakage can be minimized. It will also be important to carry to numerical modelling of seal variants in a full-scale turbine model in order to study the effect of non-stationary and non-homogeneous properties of flow in the turbine on the leakage rate.

References
[1] Kirillov I.I. The Theory of Turbomachines. Leningrad: Mechanical Engineering, 1972.
[2] Lyovochkin P.S., Chvanov V.K., Romasenko E.N., Sidorenko A.S., Kanalin Yu.I., Problems in the Development of Turbine Pump Assemblies and Booster Pumps for Modern Liquid-Propelled Rocket Engines. Moscow: NPO Energomasch, 2017.
[3] Belyaev E.N., Chvanov V.K., Chervakov V.V. Mathematical Modelling of the Working Process of a Liquid-Propelled Rocket Engine. Moscow: Moscow Aviation Institute Publications, 1999.
[4] Kanalin Yu.I., Skibin S.A., Chernysheva I.A. “Operational features of TPU turbines for the needs of an LPRE”, NTO NITs No. 769, 131, 2014 (Proceedings of NPO Energomasch), No. 32.
[5] Skibin S.A., Sternin L.E., Chernysheva I.A., Kanalin Yu.I., Poletaev N.P., Kazennov I.S., “Optimization of the construction of labyrinth turbine seals based on a spatial flow model”. NTO No. 769, 92, 2013.
[6] Kasaev Kh.V., Trofimov R.S. “Reliability of Aircraft engines”. Mechanical Engineering, 1982.
[7] Ovsyannikov B.V., Borovsky B.I., “Theory and calculation of fuel units for liquid rocket engines”. Mechanical Engineering, 1986.
[8] Timushev S.F., Klimenko D.V., Firsov V.P., Antyukhov I.V., Numerical modelling of pressure pulsations and non-stationary loads in the radial turbine of a turbo-expander”. Proceedings of the Moscow Aviation Institute, 82, 2015.