IOP Conf. Series: Materials Science and Engineering **386** (2018) 012024 doi:10.1088/1757-899X/386/1/012024

Study of factors affecting the reliability of turbochargers

L A Berdnikov, A A Pikulkin, M G Korchazhkin, P I Bazhan, L A Zakharov

Nizhny Novgorod state technical university named after R.Y. Alekseev (NSTU)

E-mail: kormg@list.ru

Abstract. The thermal loading factors of the turbocharger affecting the reliability are considered. The ways of reducing the heat load of the turbocharger elements are analyzed. The scheme of the turbocharger rotor thermal optimization, as well as options for changing the shape of the rotor. The thermal analysis of the rotor by the finite element method is performed. The temperature distribution on the surface and in the rotor section is obtained. Composed vector representation of the heat flux at the nodes of the rotor. The conclusion about the influence of changes in the shape of the turbocharger rotor on the distribution of thermal energy is given.

Turbocharger (TCR) can be attributed to those components of the car, the reliability of which is strongly determined by the operating conditions of the vehicle and maintenance. Therefore, along with the workmanship of TCR and the correct selection of the corresponding internal combustion engine, a crucial role in the extension of its service life plays the correct operation and execution. The ultimate goal of all measures taken to improve the reliability can be considered to obtain the values of the life of the TCR close to the life of the engine as a whole. Point 4.7 GOST R 53637-2009 "Turbochargers automotive" establishes the following requirement for turbochargers: the resource of the turbocharger (its service life before overhaul) should be at least the corresponding indicator of the engine.

The most important factor affecting the reliability of the transport means, regardless of the applied scheme of the installation is the thermal loading of its parts. Due to the high temperature, such failures as leaks and coking of oil, jamming and overheating of the rotor, bearing unit are common. The key places of occurrence of negative consequences of high temperatures are the labyrinth ring seals of the rotor from the turbine wheel, as well as the bearing unit. In the first case, there is the problem of separating the hot gas medium and the lubricant medium (similar to the problem of separating the combustion chamber and the crankcase space in the ice in the form of coking piston rings), and the rotor rotation speeds practically do not allow the use of other types of seals. The temperature in the area of the labyrinth seal is higher than in the bearing unit, and the oil that got into the seal does not participate in the circulation in the lubrication system of the TCR and the ice and, as a result, does not remove heat from this unit, acquiring the temperature of the surrounding parts. In the case of the bearing, there is a problem of loss of lubricating properties of the oil when exceeding the permissible temperature values in friction pairs, with further heating, wear, failure.

Oil contact with parts having a high temperature, inevitably leads to an acceleration of its aging processes. Therefore, regardless of the issue of maintaining the efficiency of the TCR, it should strive

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

for an initial approximation of the temperature of the walls of the cavities in the TCR housing to the temperature of the oil entering the TCR (90 – 110 ° C).

*There are two main ways of heat energy distribution in TCR***:**

- from the exhaust gases to the turbine part body and to the Central body;
- from the exhaust gases to the turbine wheel and further on the rotor.

Methods of reducing the temperature in the above parts of the TCR are also two: thermal insulation and cooling by means of heat removal.

Thermal insulation involves reducing the thermal conductivity of materials λ in the heat flow path. In addition, it is possible to reduce the value of the total heat flow by reducing the cross section of the part in the direction normal to the direction of the main heat flow.

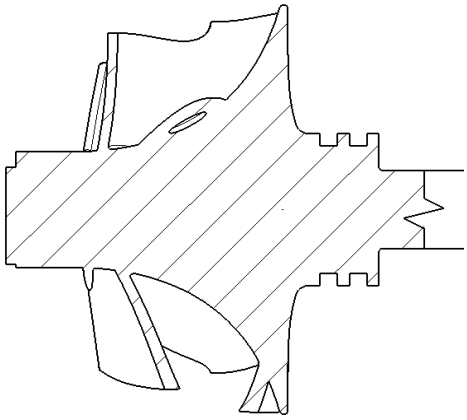


Fig. 1 Local section of the TCR rotor .

As can be seen from the figure 1, the rotor shaft in the region of grooves for labyrinth seal rings and the key points 1 and 2 considered in Fig. 2 are in close proximity to the impeller of the turbine.

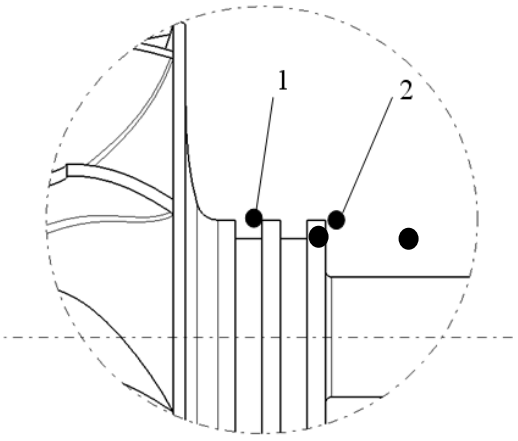


Fig. 2 Key points of the turbocharger rotor.

The latter, in turn, has direct contact with the high – speed flow of exhaust gases having a temperature of up to 700-1200 ° C depending on the type of engine. All this can cause the temperature in the areas under consideration to rise to critical temperatures in terms of oil properties. Variants of changes in the geometry of the rotor suggest the removal of heat flow from the key areas and, as a result, a decrease in the values of their temperatures.

In general, the optimization of parts under specified conditions, taking into account manufacturing techniques can be carried out by changing its geometry, changing materials (hence their properties) and a combination of these methods.

Of course, the consideration of the thermal problem for parts that experience high dynamic complex loads, in particular for the TCR rotor, is impossible without taking into account the changes in strength characteristics that change after the modification of the geometry. Therefore, it is necessary to carry out a number of strength analyses to verify the preservation of the rotor. Thus, the modification and complex analysis involves the implementation of the following scheme:

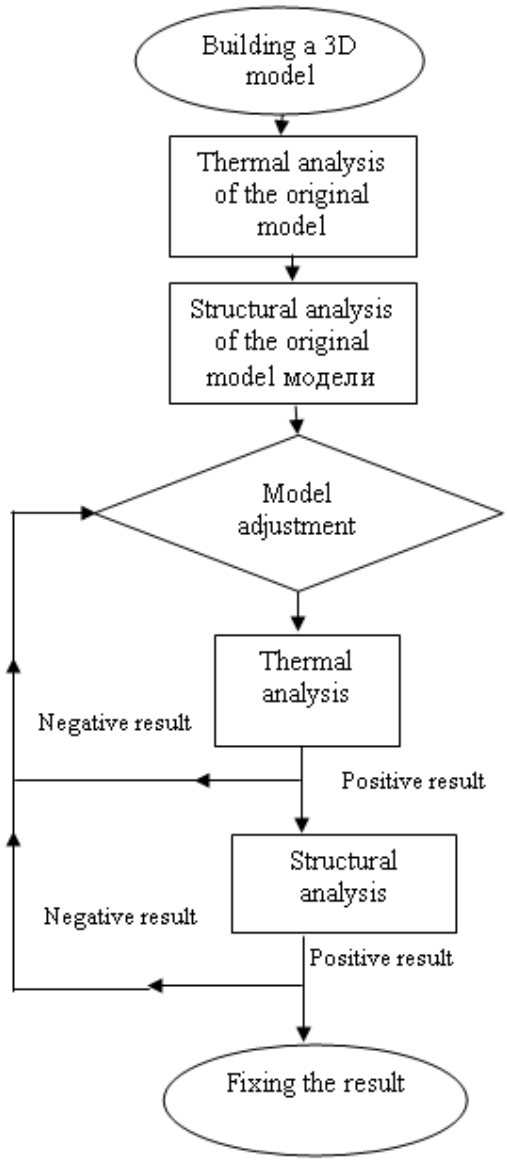


Fig.3 Simplified diagram of a thermal optimization.

A comparison method was used to assess the effectiveness of the changes. In the conducted analyses for the initial variant of the rotor and its modifications identical initial conditions, equal loads and identical structural and thermal physical characteristics of materials were set. This method allows to exclude errors when setting initial values (boundary conditions, etc.), since only the relative change of the TCR rotor parameters of interest is estimated. Despite this, the input numerical values of the initial parameters are close to the real ones, so the data obtained during the analysis can be used as indicative values.

Geometric changes of the rotor and its mass-inertia characteristics as a reduction factor

In accordance with the experience of production and operation, the shaft diameter of most turbochargers is 0.15 – 0.17 from the diameter of the compressor wheel, while there is a tendency to reduce it, because in this case, the efficiency of the TCR is increased by increasing the mechanical efficiency. The limit of shaft diameter reduction is determined mainly by technological difficulties, and not by considerations of design or operational nature, since the mechanical loads perceived by the shaft are small compared to its strength for bending and torsion. So the rotor of the turbocharger. Installed on a diesel engine with a power of 240 kW, rotates at a frequency of 60,000 min-1 and transmits a torque of about 0.5 Nm, the centrifugal forces from the residual imbalance of 0.15 g·cm do not exceed 6 N. There are already completed designs with a relative shaft diameter of 0.12, which show good reliability and durability. We present some possible variations in the rotor from a primitive rectangular groove to ducts with more complex geometry:

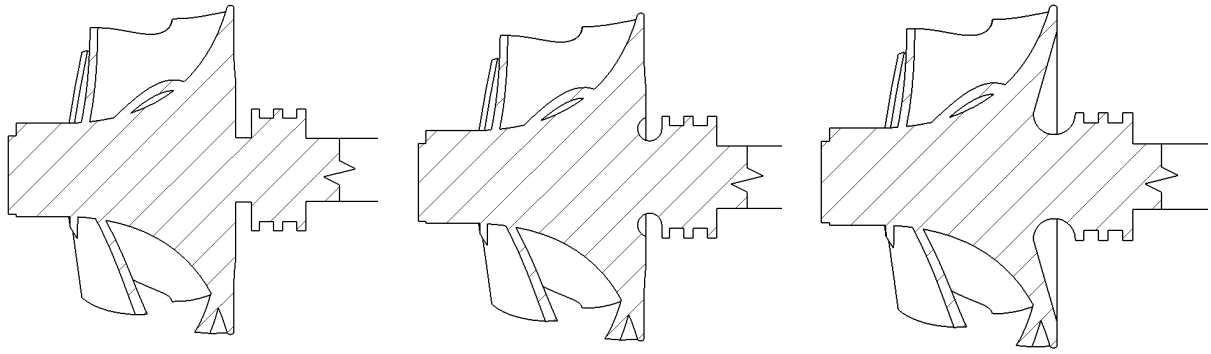


Fig. 4 Options for changing the shape of the TCR rotor.

It should be noted that the reduction of the absolute values of the size of these ducts does not make sense. This would be useful if the solution provided for a particular model of TCR were to be specified.

The most obvious impact of these changes in the form have on the mass-inertia characteristics. CATIA software allows you to quickly determine the values of these indicators when making adjustments to the original solid model.

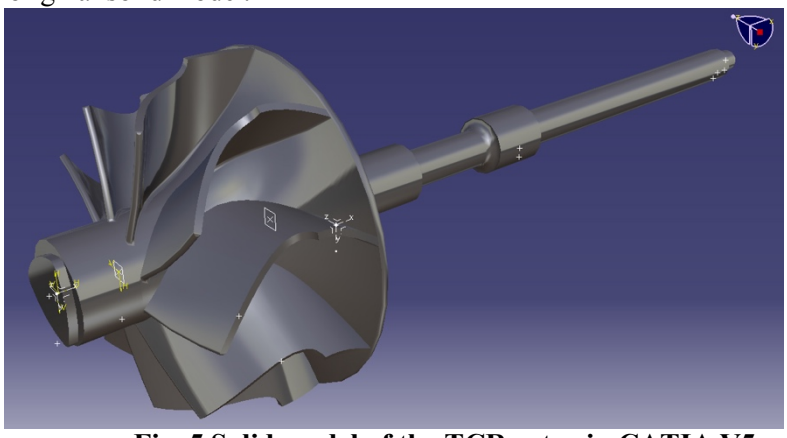


Fig. 5 Solid model of the TCR rotor in CATIA V5.

The main mass-inertial characteristics of the rotor variants at the accepted density of 7860 kg / m^3 and their relative change are summarized in **Table 1**

Table 1. Changes in the mass-inertial characteristics of the rotor

Parameters / Variant	Weight, kg	Relative change, %	Axial moment of inertia, kg·mm^2	Relative change, %
«0»	0,106	0	9,069	0
«а»	0,104	- 1,89	8,955	- 1,26
«б»	0,103	- 2,83	8,925	- 1,59
«в»	0,094	- 11,32	7,855	- 13,39

Thus, a significant change in the values of mass and moment of inertia takes place for the "в" variant. The reduction of the rotor moment of inertia has a positive effect on the turbocharger performance. The light rotor quickly increases its speed with increasing load on the engine, which increases the convenience of driving and improves the environmental performance of the engine (mainly diesel) in transient conditions by reducing the likelihood of lack of air with a sharp increase in fuel supply. Among other things, the decrease in the mass parameters of the rotor causes a decrease in the reactions of the bearing unit, for example, in the manifestation of the gyroscopic effect, which reduces the rate of wear of friction pairs.

Thermal analysis of the TCR rotor

The main purpose of the changes was to optimize the thermal condition of the rotor TCR, namely the reduction of temperatures in the zone of labyrinth seals and bearings. To analyze the effectiveness of the measures taken, a thermal analysis of the TCR rotor model was carried out using a software complex for the implementation of the ANSYS finite element method.

Stationary thermal analysis determines the steady-state temperature distribution in the structure and conductive heat flows. It is possible to set such “loads " as convective heat transfer from the surface, heat fluxes, heat flux density, heat source power and set temperatures. The analysis can be linear or nonlinear.

In the linear steady-state heat transfer process there is no influence of “thermal” masses (specific heat) and does not take into account the dependence of the thermal properties of the material on temperature. The derivative of temperature with respect to time $\{T\}$ is equal to zero, and the matrix coefficients of effective thermal conductivity is constant. In this case, the resolving equation is given by the form:

$$K] \{T\} = \{Q\}. \quad (1)$$

This system of linear joint equations is solved in one iteration and is used to calculate the processes of conductive and linear convective heat transfer.

The nonlinear non-stationary analysis of heat transfer does not consider time-dependent effects (there are no “thermal” masses). However, the thermophysical properties of materials (including the convective heat transfer coefficient from the surface) may vary with temperature; in addition, radiant heat transfer may occur.

The mechanism of radiative heat transfer is described in three different ways. A linear radiation finite element is used to model the transfer of heat by radiation between two points of space. The finite element of surface radiation is used to describe the radiation heat transfer between the surface and the point. The matrix generator is used to solve problems related to several absorbing and radiating surfaces. In the latter case, it is possible to take into account the complete or partial overlap of the surfaces, as well as to specify a node in space that absorbs or radiates energy. In the General case of heat transfer by radiation, the radiation heat flux density $\{Q\}$is a function of T^4 rather than T, i.e. the nature of the process is clearly nonlinear.

In nonlinear analysis, the thermal conductivity matrix is a function of temperature, and the solution of the problem is achieved by using iterations. In the program ANSYS, the iterative procedure has its main Newton-Raphson method, which involves solving a sequence of linear problems to obtain a

nonlinear approximation. Thus, the equation for the nonlinear stationary heat conduction problem has the form

$$[K]_i \{\Delta T\}_{i+1} = \{Q^A\} - \{Q^{NR}\}_i, \quad (2)$$

where i is the iteration number.

This equation is solved in the first iteration at some initial temperature (which can be set by the user); in subsequent iterations, the temperature values obtained in the previous iteration are used to calculate the thermal conductivity matrix coefficients. The iteration process continues until the convergence of the solution is reached, i.e. until the user-defined convergence criterion is met. The convergence is controlled by the magnitude of the load vector residual (heat flow) and/or temperature change from iteration to iteration.

The solution results, for linear and nonlinear analysis, represent the temperature and heat flux density values at the nodes. These data can be used in post-processing to build a picture of isotherms in the computational model. Postprocessor tools can be used to obtain such specific information as the values of temperature gradients or flows in the nodes and in the center of the element, as well as the density of the heat flux through the radiation (absorption) surface. The information is displayed in tabular or graphical form.

Some assumptions were made in this analysis:

- there is only convective heat transfer, other types of heat transfer are taken into account by the heat transfer coefficient ; thus, the initial conditions are the boundary conditions of the third kind;
- a simplified model of the rotor (without impeller blades) is considered, which does not affect the result in the form of a picture of temperature fields;
- preliminary calculations revealed the absence of heat exchange effect in the part of the rotor shaft, which has contact with the compressor wheel and the air inlet flow; further calculations are carried out with the simplification of convective heat transfer in this part in the form of setting the same boundary conditions as the bearing part of the rotor;
- heat generation in friction pairs is negligibly low.

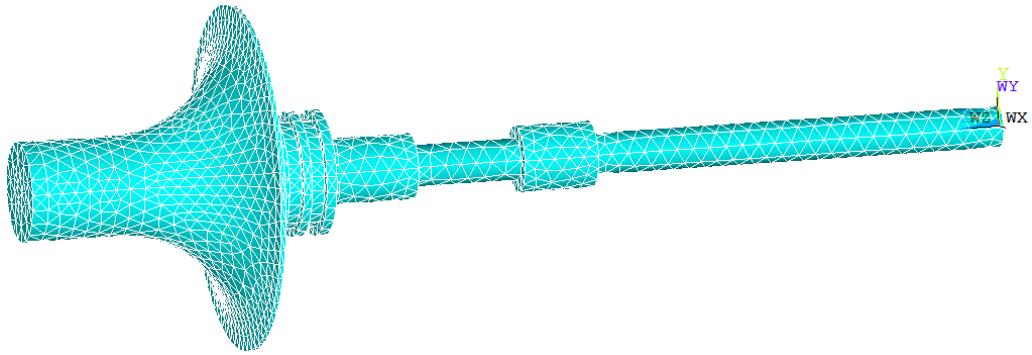


Fig. 6 Simplified solid rotor model with finite element mesh.

The analysis uses an arbitrary grid of finite elements-tetrahedra with a linear size of parabolic edges up to 1.5 mm, which provides the necessary accuracy of the solution at an acceptable computation time.

The analysis of any type requires specifying the properties of the material. The model used data tables for two materials-heat-resistant Nickel alloy turbine wheel and carbon steel shaft. The software package ANSYS provides the ability to take into account the dependence of the properties of materials on temperature. The properties of the materials are isotropic. Data on the characteristics of the materials are presented in table 2

Table 2. Determination of material properties.

Temperature: ºC / Characteristic for materials I and II:		20	100	200	300	400	500	600
Density, kg/m^3	I	8450	8442	8431	8420	8408	8395	8383
	II	7820	7800	7770	7740	7700	7670	7630
Specific heat, j/(kg ·ºC)	I	538	575	609	634	676	735	782
	II	472	482	496	513	532	555	583
Thermal conductivity, $\frac{Vt}{m \cdot °C}$	I	7,9	8,8	10,5	11,8	13,8	15,9	18,4
	II	53	50,2	46	41,9	37,7	33,5	29,3
The modulus of elasticity, hPa	I	210	206	202	198	193	188	182
	II	215	210	205	200	190	180	170
Expansion coefficient $\alpha \cdot 10^5$ 1/ºC	I	1,2						
	II	1,3						

I - heat-resistant nickel alloy, II - steel

Boundary conditions in the analysis are set for surfaces and include the temperature of the medium (liquid or gaseous) T_f washing the surface and the generalizing heat transfer coefficient α, taking into account both the nature of the medium flow around the surface and its thermal properties. The boundary conditions for thermal analysis are shown in figure 3.7:

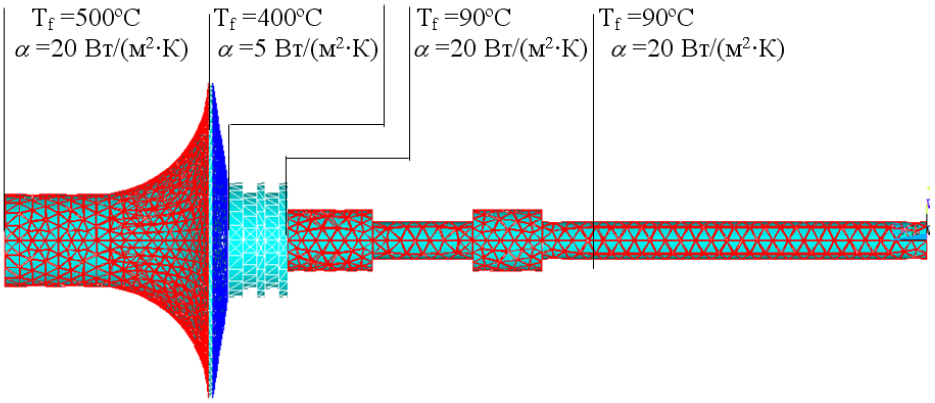


Fig. 7 Boundary conditions in thermal analysis.

Thus, a solid model with finite element partitioning, given material properties and boundary conditions form the basis for the implementation of the finite element method algorithm and obtaining the required results.

The main purpose of the analysis is to obtain the temperature distribution and the nature of the flow of heat in the rotor body for different variants of its shape. Changes in these parameters when modifying the geometry under similar initial conditions allow to draw conclusions about the impact of these changes in geometry on the thermal state of the rotor. We present the results of stationary thermal analysis of rotor variants starting from the initial modification. In figures (8-9) - the temperature distribution on the surface and in the rotor section, as well as the vector representation of the heat flow in the element nodes.

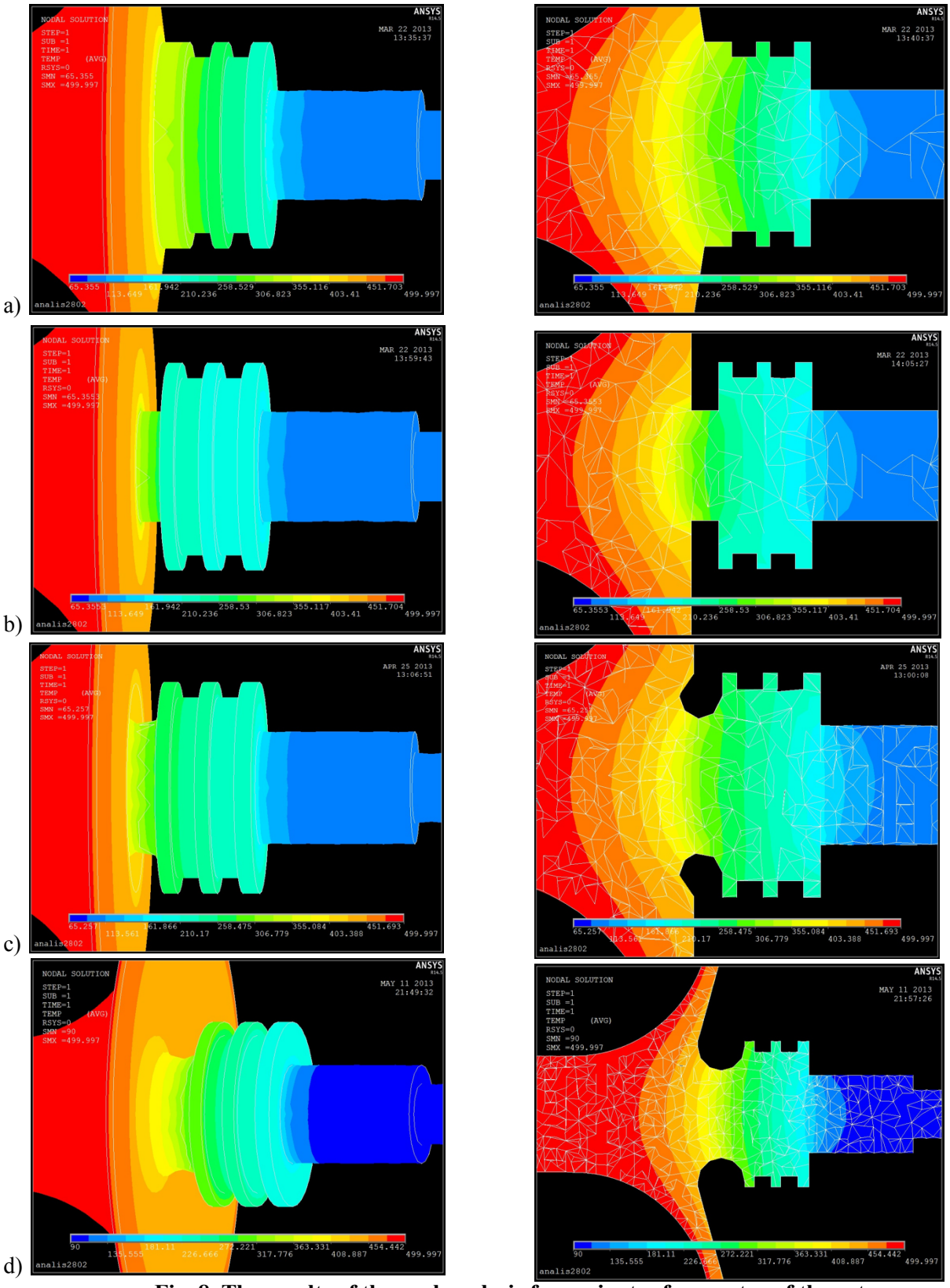


Fig. 8 The results of thermal analysis for variants of geometry of the rotor.

To facilitate the representation of the nature of the heat flow in the rotor body, let us present its vector visualization. The results are presented with different densities of vectors.

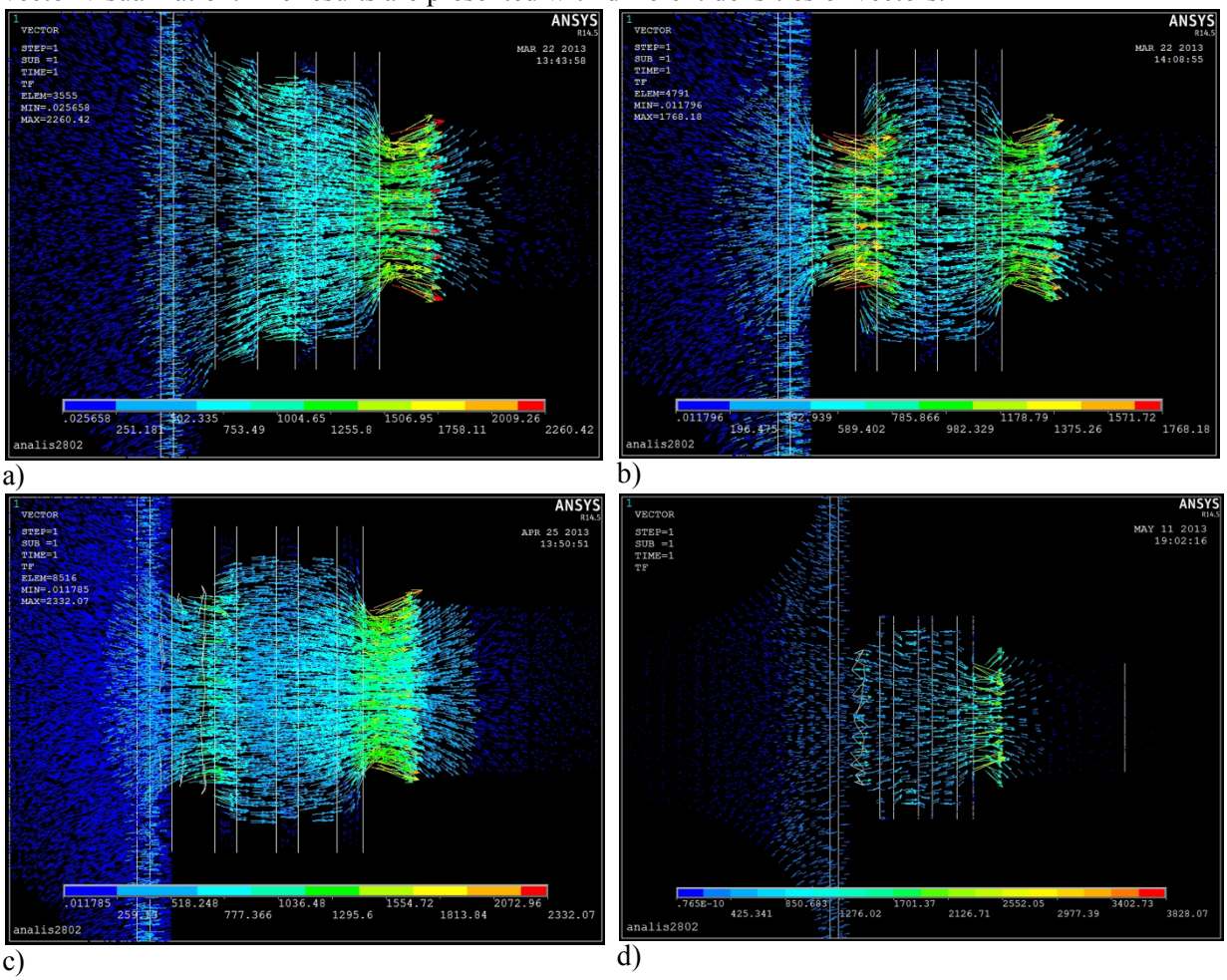


Fig. 9 Vector representation of heat fluxes in the rotor body (with different vector densities).

The results of the temperature ranges for key points 1 and 2 are summarized in table 3

Table 3. Thermal analysis results for rotor shape options

Zone	Variant:	0)	A)	Б)	В)
T.1	Temperature, ºC	306 - 330	210 - 234	258 - 282	272 - 294
	Relative change, %	0	- 30,2	- 15,1	- 11,0
T.2	Temperature, ºC	210 - 234	185 - 210	210 - 234	204 - 226
	Relative change, %	0	- 11,0	0	- 3,1

The results suggest that the most effective way to reduce the temperature in the key areas is option (а), which can be explained by the smallest cross section in the heat flow path. Options б) and в) are also effective and contribute to a significant reduction in heat flow from the turbine wheel to the rotor shaft.

Thus, the shape change has a significant impact on the distribution of heat energy, allowing to reduce the temperature in the areas of interest. The ability to reduce temperatures by changing the shape of parts is limited by the strength characteristics. To assess the influence of the part shape on its structural qualities, it is necessary to conduct a number of subsequent analyses.

References

[1] Berdnikov, L. A., Suvorov I. A., Vilkov, N. A.. An integrated approach to the consideration of the factors determining the reliability of turbochargers of automobile ice. Collection of materials 12 International youth scientific and technical conference "the Future of technical science", Nizhny Novgorod NSTU 2013- p. 195-196

[2] Berdnikov, L. A., Suvorov I. A. "Study of the possibility of thermal optimization of the turbocharger rotor with the conduct of finite element analysis. The works of NSTU No. 4, 2013 p. 56-65»

[3] Berdnikov, L. A., Suvorov I. A. "Improvement of temperature condition of automobile engine turbochargers." Moscow. Motor transport enterprise. No. 4. April 2014-p. 40-42

[4] Berdnikov, L. A., Suvorov I. A., Kuzmin N. A., Thermal insulation screen of the turbocharger. Patent № 141164, Russia 22.04.2014

[5] Berdnikov, L. A., Suvorov I. A., The rotor shaft of the turbocharger. Russia, from 01.06.2015

[6] Berdnikov, L. A., Suvorov I. A., Design to prevent oil from burning in the turbocharger. Patent No. 159068. Russia 17.06.2015