MACHINE BUILDING AND MACHINE SCIENCE

UDC 621.65; 004.92 https://doi.org/10.23947/2687-1653-2021-21-1-71-81

Strength analysis of the TWS 600 plunger pump body in Solid Works Simulation

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Introduction. The relevance of the presented paper is due to the widespread use of plunger pumps in industrial practice, in particular, in gas and oil production. The quality of working operations and the efficiency of further well operation depend largely on their reliability. The improvement of plunger pumps involves increasing their reliability, increasing their service life, efficiency, downsizing, reduction in weight, labor intensity of installation and repair work. The modernization of the mechanism includes its power study since the found forces are used for subsequent strength calculations. Before the appearance of programs for the numerical analysis of solid objects, the analytical solution to the problem of strength calculation of the high-pressure pump drive frame was a very time-consuming and expensive procedure. The situation has changed with the development of computer technologies and the inclusion of the finite element method in the computer-aided design systems. The objective of this work is to perform a strength calculation on the TWS 600 plunger pump body made of 09G2S steel.
Materials and Methods. A method for determining the reactions of the crank shaft supports of a high-pressure plunger pump and strength calculation of the drive part housing is developed. The direction and magnitude of the resulting forces and reactions of the supports are determined graphically according to the superposition principle of the force action on the supports. Strength calculations were performed using the finite element method in the computer-aided design system Solid Works Simulation. In this case, solid and finite-element models of the body with imposed boundary conditions were used, which were identified during the analysis of the design and the calculation of the forces arising under the pump operation.
Results. The reactions in the crankshaft supports are described with account for the forces generated by the plunger depending on its operating mode and the crank position. The forces acting on each of the plungers and the resulting reactions in each of the supports are determined. The diagrams of stresses and the safety factor are presented, which provide assessing the strength of the body and developing recommendations for creating a more rational design.
Discussion and Conclusions. As a result of the calculations, we have identified areas of the structure with minimum safety factors, and areas that are several times higher than the recommended values. This provides optimizing the design under study through strengthening the first and reducing the thickness of the metal on the second. From the point of view of weight and size characteristics and maintainability, the results of the strength calculation performed can be used to optimize the design of the pump body under typical operating conditions.

***Keywords**:* plunger pump, support reactions, strength calculation, design optimization, superposition principle, calculation of body parts.

For citation: E. V. Koleda, S. O. Kireev, M. V. Korchagina, et al. Strength analysis of the TWS 600 plunger pump body in Solid Works Simulation. Advanced Engineering Research, 2021, vol. 21, no. 1, p. 71–81. https://doi.org/10.23947/2687-1653-2021-21-1-71-81

Funding information: the research is done within the frame of the independent R&D no. AAAA-A20-120012190068-8 of 21.01.2020.

Introduction. Oil production is not complete without the use of plunger pumps. They are required for such working operations as well cementing and acidizing, sand blast perforation, hydrofracturing, etc. [1]. Downsizing and reduction in weight of the pumps make them extremely attractive for use in mobile oilfield installations. The reliability of the pumps largely determines the quality of processing and the efficiency of further operation of oil and gas wells [2].

Despite the overall rather high level of plunger pump designs, they continue to be improved. The improvement of plunger pumps involves increasing their reliability, increasing their service life, efficiency, downsizing, reduction in weight, labor intensity of installation and repair work. For this purpose, the designs of the components and parts of the drive and hydraulic systems are changed [3-5]. The modernization of the mechanism includes its power study since the found forces are used for subsequent strength calculations. Recently, in connection with the development of computer technologies, numerical methods of strength analysis with the use of applied programs are increasingly used [6, 7].

Before the appearance of programs for the numerical analysis of solid objects, the analytical solution to the problem of strength calculation of the high-pressure pump drive frame was a very time-consuming and expensive procedure [8-10]. The development of the finite element method (FEM) in the deformable solid mechanics and its inclusion in computer-aided design systems (CAD, e.g., Solid Works Simulation) opens up new opportunities in solving problems of this kind. Strength calculations performed in CAD provide optimizing the design of the body parts. For the design under consideration, the body is one of the critical parts that takes up the load and provides the correct mutual arrangement of the drive part elements.

To obtain reliable results in the strength analysis of the pump body using numerical methods in CAD, it is required to determine all external loads acting on the body.

The widely used TWS 600 triplex plunger pump was selected as the object of modernization. In Russia, structural low-alloy 09G2S steel is used for manufacturing body parts of high-pressure plunger pumps [11]. Replacing the material of the body parts of TWS 600 plunger pump with 09G2S steel will reduce the cost. In this regard, this work objective is to analyze the possibility of replacing the material of the body of TWS 600 plunger pump with 09G2S steel to optimize the price and provide the possibility of repair work.

Materials and Methods. The replacement of the material should be validated by the strength calculation. The calculation of the body was carried out by the FEM in the CAD Solid Works Simulation.

The external forces acting on the pump body are reactions in the crankshaft supports. They arise from the action of the inertia forces of the reciprocating moving parts of the crosshead connecting rod group and the forces of fluid pressure on the plunger. To determine the reactions in the crankshaft supports, it is required to perform a dynamic calculation of the slide-crank mechanism of the plunger pump[1].

As mentioned in [12, 13], tasks of the dynamic analysis include studying the influence of external and internal forces on the links and kinematic pairs of the mechanism, as well as identifying ways to reduce dynamic loads.

The crankshaft in question consists of two main journals on the major shaft axis and three crank journals eccentrically arranged at 120° offset. The bearing supports are located on the main journals and on the crank webs between the crank journals (Fig. 1).

[1] Timofeev GA. Theory of machines and mechanisms: a course of lectures. Moscow, 2010. 351 p. (In Russ.)

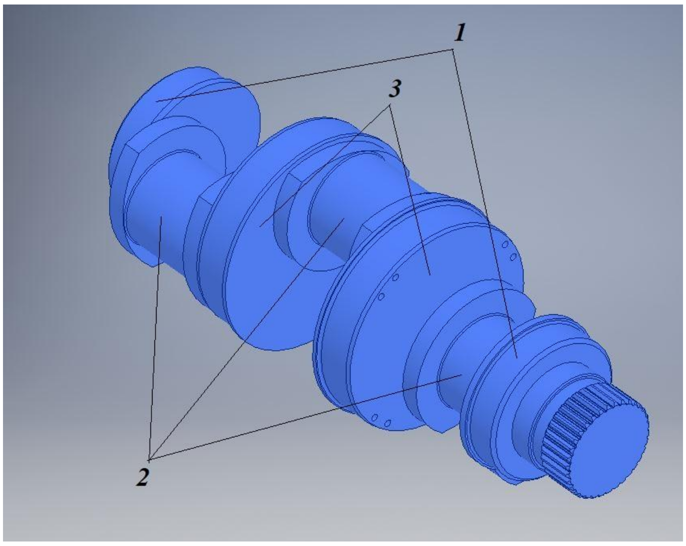


Fig. 1. Crankshaft of TWS 600 plunger pump: 1 — main journals; 2 — crank journals; 3 — webs

During the operation of the pump, three plungers reciprocate successively to provide discharge or suction (Fig. 2).

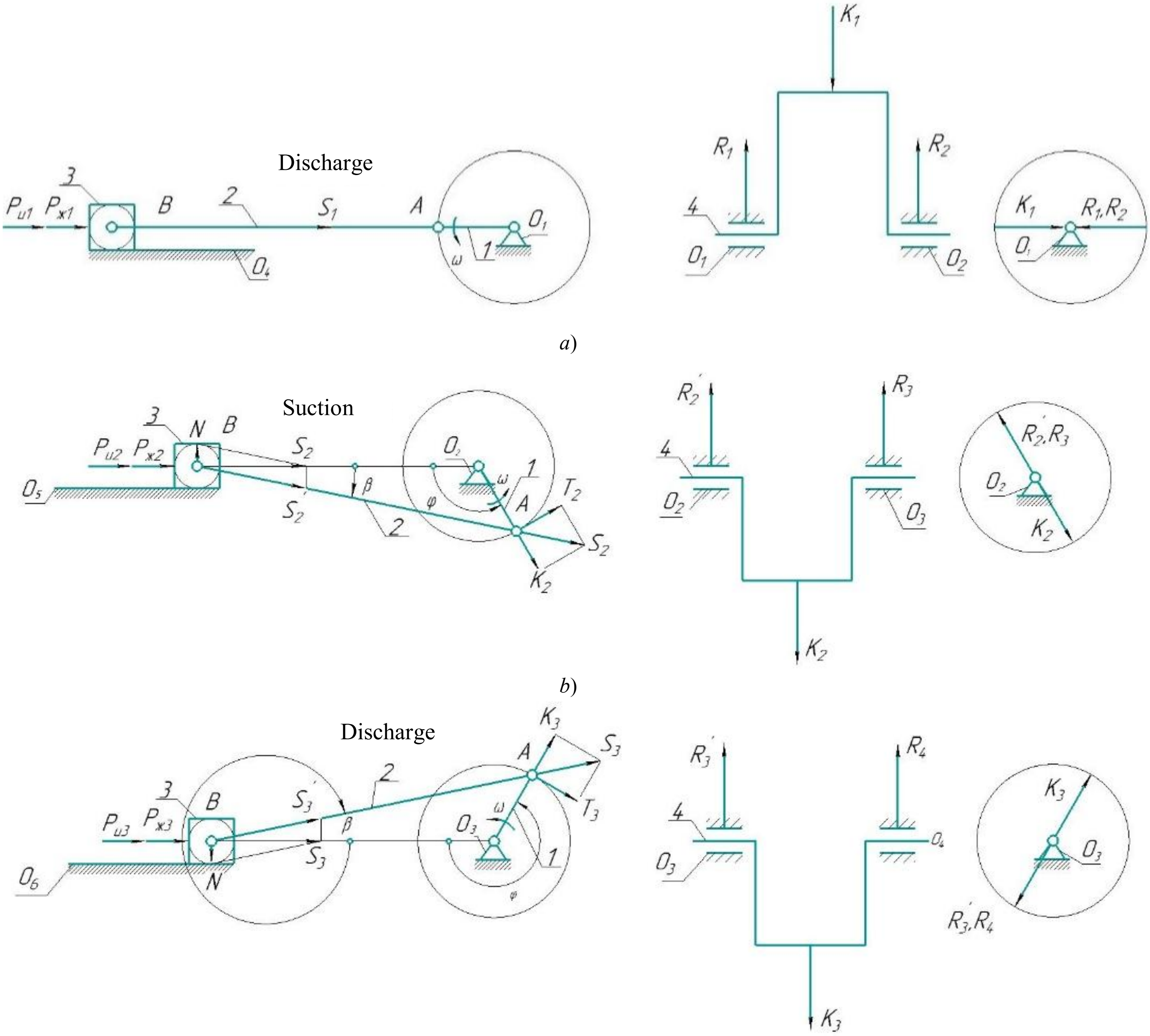


Fig. 2. Design diagram of the mechanism of the drive part of the plunger pump: *a*) position of the 1st plunger; *b*) position of the 2nd plunger; *c*) position of the 3rd plunger

Consider the position of the mechanism in which the first plunger is located at the extreme discharge point (ex. p.) and is under maximum load. The angle of rotation of the crank journal for this plunger is zero (Fig. 2 *a*). Then, the second plunger performs suction (Fig. 2 *b*), its journal is displaced by 120°. The third plunger operates for the discharge (Fig. 2 *c*), the journal is displaced by 240°. Thus, in one situation, the crankshaft is loaded with forces of different magnitude, and the reactions of the supports will be different. This occurs when the crank is in the position when the first plunger is at the extreme point of discharge, the second performs suction, and the third operates for discharge. We will perform the calculation for the specified position of the crank (mechanism) [8-10], and then, for other positions: when the second and third plungers will reach the extreme discharge point.

Link masses were calculated in the Autodesk Inventor Professional 2018 program based on the previously created 3D model of the drive of the TWS 600 plunger pump. A design diagram of the mechanism of the drive part of the plunger pump was constructed with an indication of the forces acting on its links (Fig. 2).

Let us denote the external forces for finding the crank shaft reactions: $P_ж$ — fluid pressure force, P_u — inertia force.

The fluid pressure force acting on the plunger is found from the expression:

$$P_ж = p_ж \cdot \pi \cdot r^2,$$

where $p_ж$ — pressure of the pumped liquid applied to the plunger; r — radius of the section of the plunger[1].

The inertia force of the reciprocating moving parts is:

$$P_u = -m \cdot i = -m \cdot r \cdot \omega^2 \cdot (cos\varphi + (2 \cdot cos^2\varphi - 1),$$

$$m = m_k + 0{,}275 \cdot m_ш,$$

where m_k — crosshead mass, $m_ш$ — mass of the upper connecting rod head, r — crank radius, ω — crankshaft speed at 230 rpm, φ — crankshaft angle.

The force acting on the plunger is determined from the formula:

$$P_\Sigma = P_{жi} + P_{ui},$$

where $P_{жi}$ — pressure force of the pumped liquid in each position of the plunger, P_{ui} — inertia force of the reciprocating moving parts in each position of the plunger.

Total force P_Σ, applied to the crosshead pin axis and directed along the axis of the cylinder, can be decomposed into:

— force *N* acting perpendicular to the axis of the cylinder;

— force *S* acting on the axis of the connecting rod.

N presses the crosshead against the cylinder wall, which causes wear on their surfaces. This force changes in value and direction, alternately pressing the crosshead to one or the other side of the guides.

The force *S*, transferred to the of the crankpin axis, can be decomposed into:

— tangential force *T*, acting perpendicular to the crank of the crankshaft;

— radial force *K*, directed along the crank axis.

The force *K* is determined from the formula:

$$K_i = P_{\Sigma i} \cdot \frac{\cos(\varphi_i + \beta_i)}{cos\beta},$$

where φ_i — crank angle (Fig. 2); β_i — angle of deviation of the connecting rod from the axis (Fig. 2); $P_{\Sigma i}$ — total force acting on the plunger.

The results of calculating radial forces for all crank journals in each considered position of the mechanism are summarized in Table 1.

[1]Catalog of high-pressure plunger pumps manufactured by Weir SPM, Nord-SPM LLC. URL: http://виерспм.рф/catalogues/JI2IK_КАТАЛОГ НАСОСОВ.pdf (accessed: 14.02.2021). (In Russ.)

Table 1

The results of calculating radial forces for all crank journals
in each considered position of the mechanism

Mechanism position								
I			II			III		
Plunger position								
1	2	3	1	2	3	1	2	3
ex.p.	suction	discharge	discharge	ex.p.	suction	suction	discharge	ex.p.
φ, degree								
0	120	240	240	0	120	120	240	0
K, H								
450000	–2503	–306687	–306687	450000	–2503	–2503	–306687	450000

The reactions of the supports are directed opposite to the radial forces (Fig. 3), and their values are determined from the formulas:

$$R_1, R_2 = \frac{K_1}{2},$$
$$R_2', R_3 = \frac{K_2}{2},$$
$$R_3', R_4 = \frac{K_3}{2},$$

where K_1, K_2, K_3 — radial forces directed along the crank axis.

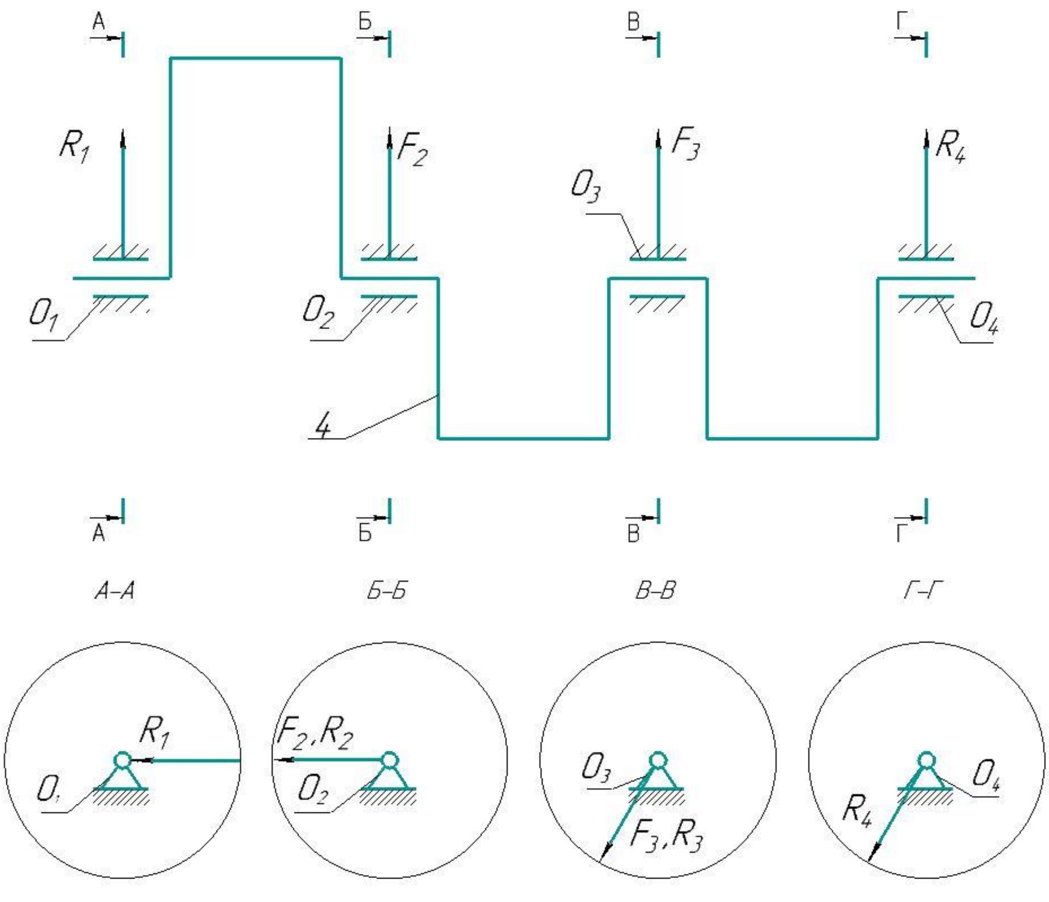


Fig. 3. Scheme of reactions of supports

The direction and magnitude of the resulting forces F_2 and F_3 of the reactions of the supports O_2, O_3 re determined graphically (see Fig. 3) according to the principle of superposition of the force action on the supports.

The resulting forces F_2 and F_3 coincide in magnitude and direction with the forces R_2 and R_3', respectively.

Numerical values and directions of reference reactions are found for the position of the mechanism at which the first plunger was at the discharge extreme point (see Fig. 2 *a*), the second performed suction (see Fig. 2 *b*), and the third — discharge (Fig. 2 *b*). For other positions of the mechanism, the reactions of the supports are determined similarly and will be numerically equal, alternately changing places.

Table 2 shows the results of calculating the reactions of the crankshaft supports for the positions of the mechanism in which each of the plungers is alternately located at the extreme discharge point.

Table 2

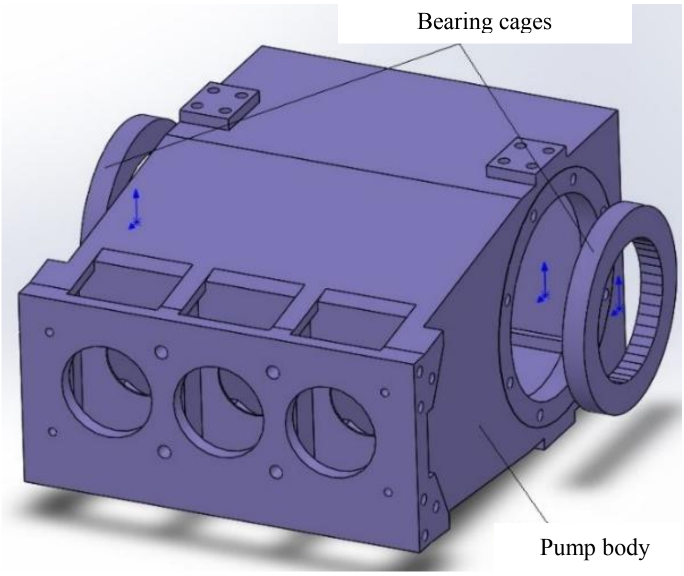
Numerical values of the reactions of the supports for all positions of the mechanism

Mechanism position	Plunger position			Reaction forces of the supports			
				R_1, H	F_2, H	F_3, H	R_4, H
I	1	2	3	225000	225000	153343	153343
	ex.p.	suction	discharge				
II	1	2	3	153343	329602	225000	1251
	discharge	ex.p.	suction				
III	1	2	3	1251	153343	329602	225000
	suction	discharge	ex.p.				

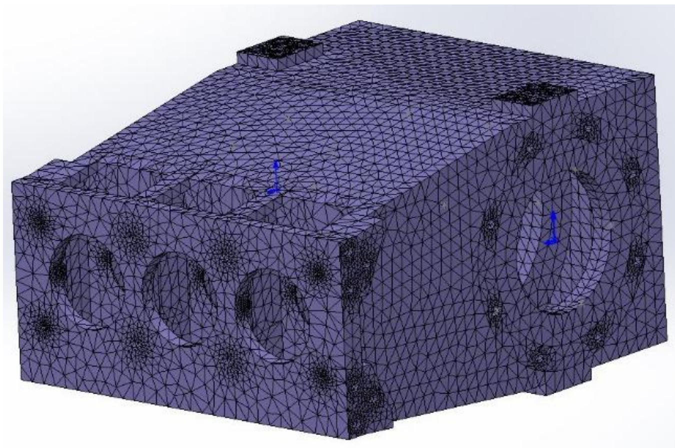
The body of the high-pressure plunger pump was modeled in Autodesk Inventor Professional 2018 CAD system. The model includes bearing cages since the presence of a cage significantly affected the nature of the load application.

The strength analysis is performed by the FEM in the computer-aided design system Solid Works Simulation.

Fig. 4 *a* shows a solid model of the calculated structure, and Fig. 4 *b* shows a finite-element model.



a)



b)

Fig. 4. Body models of the TWS 600 three-plunger high-pressure pump: *a*) solid-state, b) finite-element

The finite element model contains 100,747 elements (175,172 nodes). The body material is 09G2S steel. The model describes the loads and records the movements in all directions of the surfaces of the bolt holes. Fig. 5 shows the boundary conditions for the contacting surfaces. By the type of contacts, the surfaces are connected to common nodes.

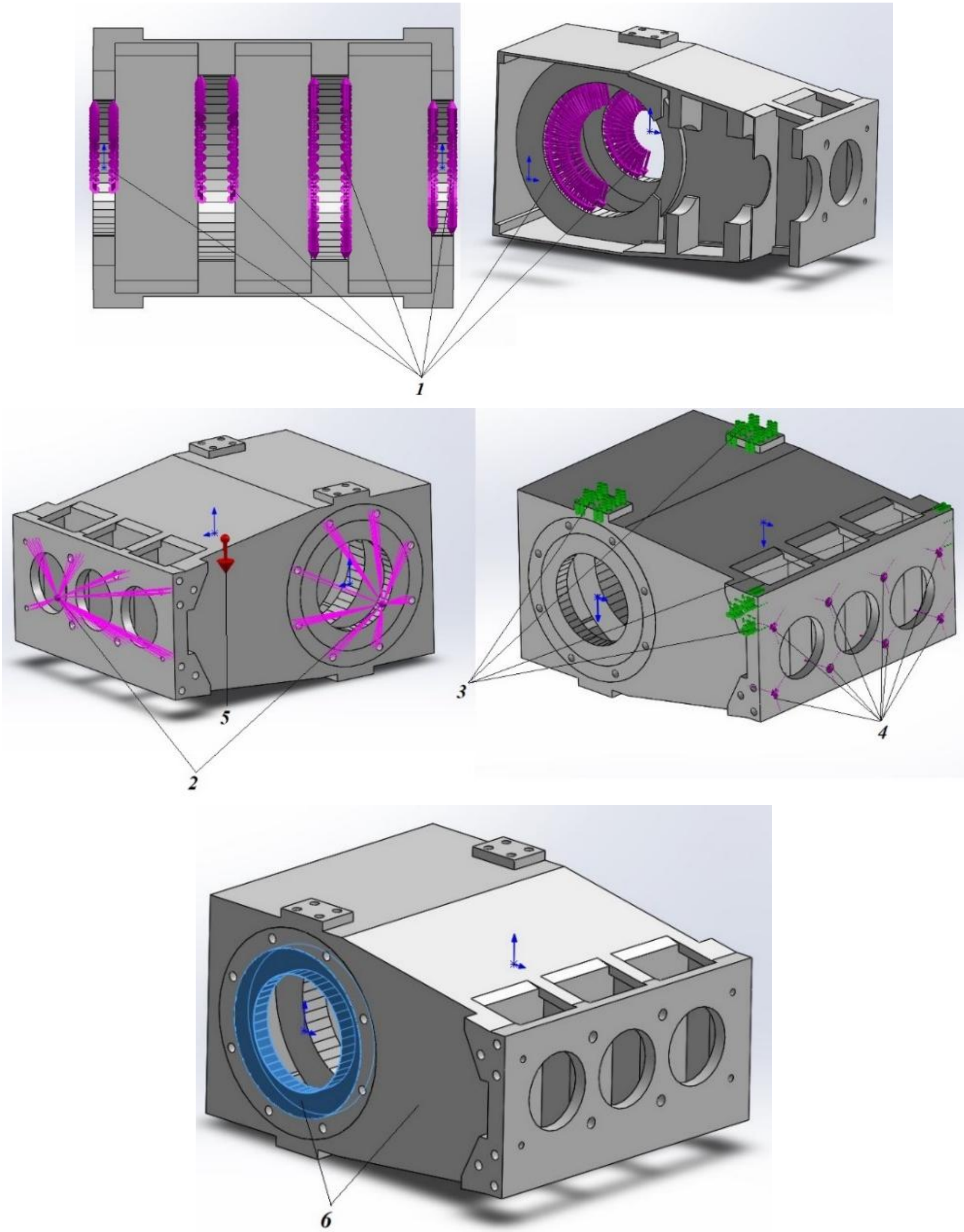
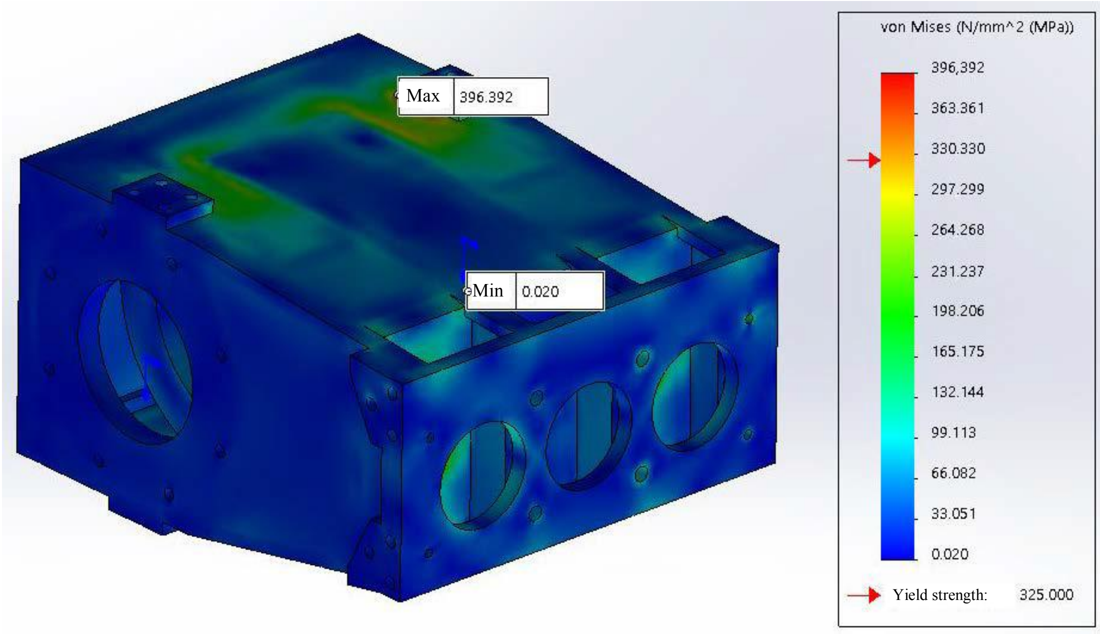
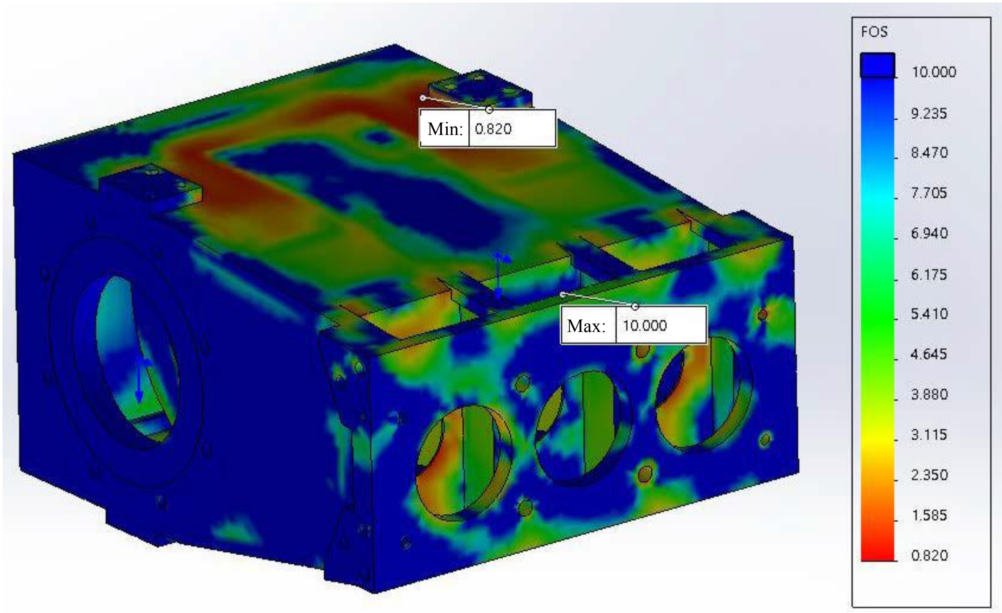


Fig. 5. Boundary conditions: 1 — operating load (radial force distributed over cylindrical surfaces); 2 — remote loading (mass of the gearbox and hydraulic unit); 3 — restriction — “fixed”, zero movements in all axes — *X*, *Y*, *Z*; 4 — operating load (pressure force of the liquid under discharge and suction); 5 — gravity; 6 — type of contact — connected (no gap) surfaces with shared nodes

Research Results. Diagrams of equivalent von Mises stresses are shown in Fig. 6.



a)



b)

Fig. 6. Diagrams obtained as a result of the strength analysis of the TWS 600 plunger pump body: *a*) diagram of equivalent stresses, *b*) diagram of the yield factor

Yield factor is determined from the formula:

$$K_{\text{п}} = \frac{\sigma_{\text{в}}}{\sigma_{\text{экв}}},$$

where $\sigma_{\text{в}}$ — ultimate strength of 09G2S steel, $\sigma_{\text{в}} = 470$ Mpa[1]; $\sigma_{\text{экв}}$ — maximum equivalent stress, $\sigma_{\text{экв}} = 396.392$ MPa.

$$K_{\text{п}} = \frac{470}{396{,}392} = 1{,}18.$$

As can be seen, the equivalent stresses[2] have the greatest intensity in the lower region of the pump body design.

The minimum yield factor of the material is 0.82 (see Fig. 6 *b*).

[1] Zubchenko AS, Koloskov MM, Kashirsky YV, et al. Steel and Alloy Grade Guide. Moscow, 2003. 784 p. (In Russ.)
[2] Feshchenko VN. Constructor reference. Book 2. Design of machines and their parts. Moscow, 2017. 400 p. (In Russ.)

The strength calculation of the plunger pump body was carried out for the third position of the mechanism (Fig. 2 *b*). For other positions of the mechanism (see Fig. 2 *a, b*) the strength calculation is performed similarly.

The results of the strength calculation of the body for the three positions of the mechanism are shown in Table 3.

Table 3

Results of the strength calculation of the plunger pump body

Mechanism position	Plunger position			Equivalent stresses, MPa	Safety factor for	
					yield strength	ultimate strength
I	1	2	3	231.772	1.402	2.02
	ex.p.	suction	discharge			
II	1	2	3	284.783	1.141	1.65
	discharge	ex.p.	suction			
III	1	2	3	396.392	0.820	1.18
	suction	discharge	ex.p.			

Discussion and Conclusions. The reactions in the crankshaft supports with account for the forces generated by the plunger depending on its operating mode and the position of the crank are described. The forces acting on each of the plungers and the resulting reactions in each of the supports are determined.

For the strength calculation of the plunger pump body made of 09G2S steel, the FEM in CAD SolidWorks Simulation is used. When assessing the body strength, it has been observed that in the third position of the mechanism, the lower region of the structure has minimum coefficients of yield factor and strength factor (see Table 3). This area requires strengthening since the coefficient values are insufficient for the specified operating conditions. Also, there are unloaded areas in the body, where the values of safety and yield factors are several times higher than the recommended ones. In the future, it is required to optimize the plunger pump body: to strengthen the areas of the structure with unsatisfactory coefficients of safety and yield factors, and in places where the coefficients exceed the recommended values, to use a metal of a smaller thickness.

Thus, the strength calculation results can be used to optimize the design of the pump body under standard operating conditions.

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Submitted 24.01.2021

Scheduled in the issue 27.02.2021

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Claimed contributorship

E. V. Koleda: computational analysis; text preparation; formulation of conclusions. S. O. Kireev: academic advising; basic concept formulation; research objectives and tasks. M. V. Korchagina: analysis of the research results; the text revision; correction of the conclusions. A. V. Efimov: supervising the model construction; monitoring the implementation of numerical studies. Joerg Sperling: statement of the research problem; scientific advice.

All authors have read and approved the final manuscript.