Наведено результати досліджень герметизаційної здатності самоущільнювальних манжет свердловинних випробувальних пакерів. Розроблено статистичну математичну модель визначення контактних тисків з урахуванням силових факторів, геометричних характеристик ущільнення та фізико-механічних властивостей матеріалу манжети. Експериментально встановлено закономірності розподілу контактних тисків по довжині спряженої поверхні: манжета – обсадна труба

Ключові слова: свердловинний пакер, самоущільнювальна манжета, контактні тиски, противикидне обладнання, гирлове обладнання, модуль зсуву

Приведены результаты исследований герметизационной способности самоуплотнительных манжет скважинных испытательных пакеров. Разработана статистическая математическая модель определения контактных давлений с учётом силовых факторов, геометрических характеристик уплотнения и физико-механических свойств материала манжеты. Экспериментально установлены закономерности распределения контактных давлений по длине сопряжённой поверхности: манжета – обсадная труба

Ключевые слова: скважинный пакер, самоуплотнительная манжета, контактные давления, противовыбросовое оборудование, устьевое оборудование, модуль сдвига

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EXPERIMENTAL RESEARCH ON THE SEALING ABILITY OF BOREHOLE PACKERS

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1. Introduction

Special devices known as packers are used to detach individual sections of oil and gas wellbores for their repairing or operation or for checking the impermeability of blowout preventers and wellhead equipment. Their main sealing element is rubber [1]. Preferred packers are based on self-sealing rings that are automatically triggered by an excess pressure of a test fluid in the space above the packer; they are simple to use and highly impermeable.

The current world market of equipment for the construction or operation of oil and gas wells is characterized by a variety of packers on the basis of self-sealing rings. The Ukrainian most successful design of a packer is a UHF type manufactured by a special rescue service SE "LIKVO" (Kharkiv, Ukraine (Fig. 1, *a*, *b*)) [2]. The packer, which is based on a rubber self-sealing ring, is designed to test blowout preventers and wellhead equipment during underground repair work of wells.

Given that impermeability of borehole packers is a comprehensive measure of their technical characteristics, its research is in a particular focus of scientists.

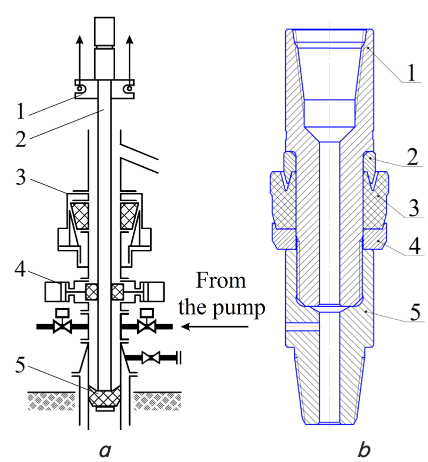


Fig. 1. A wellhead packer of a UHF type: *a* – a flowchart of testing a spot preventer using a packer (1 – an elevator, 2 – a pipe, 3 – a universal preventer, 4 – a spot preventer and 5 – a packer); *b* – a constructive design of the packer (1 – the packer mandrel, 2 – a thrust bush, 3 – a self-sealing ring, 4 – a seat and 5 – an adapter)

2. Analysis of previously published data and a statement of the problem

Impermeability of borehole packers is researched nowadays for their various designs and in different directions.

The authors of [3] conducted experimental tests to determine rational conditions for the sealing ability of the compression element of a borehole packer. The object of the study was borehole packers based on cylindrical seals; their sealing mechanism consists in a radial deformation of the seal at its axial compression by an external force. Certain dependence was found between contact pressure on a conjugate surface of the seal and the casing column and the test pressure. However, the obtained research results cannot be used for constructing self-sealing rings of test wellhead packers that automatically start working under applied pressure.

In [4, 5], there are constructive descriptions of test packers that are based on self-sealing rings, with some practical recommendations to improve their tightness during the trial of blowout preventers and wellhead equipment. In particular, based on operating experience, some information is provided about a rational tension of the ring [5] and recommendations are given on a radial clearance between the focusing unit of the seal and the casing wall [4]. Meanwhile, the practical experience of using the self-sealing packer unit described in [5] reveals the need to create pulse loads (an injection of test fluid at high performance of pump units) for the start-up operation of the sealing ring and achieving pressurization during the test. This trial mode is caused by a rather small tension of the self-sealing ring and, thus, lack of sufficient initial contact pressure q_0. Given the small installation depth for test packers with self-sealing rings and, consequently, a limited area of the annulus into which the test fluid is injected, there is a possibility of destroying the equipment and injuring the workers under conditions of pulse loads.

It is noteworthy that the working principles of self-sealing rings that are used in general engineering and the self-sealing rings of the tested borehole packers are almost the same. It is, therefore, worthwhile to perform a comparative overview and analysis of these analogues.

In [6], rubber rings of hydraulic power cylinders have been experimentally proven to exhibit nonlinear relationships between the test pressure and the size of the radial clearance, namely between the focus and the wall of the hydraulic cylinder and the size of the ring material that it pressed out into a clearance during its work.

The authors of [7] point out a dependence of the initial contact pressure q_0 of self-sealing rings on the size of the initial tension, which is directly proportional.

In [8, 9], there is a flowchart of distributing specific contact pressure on the conjugate surface of the ring: between the outer lip and the cylinder. Moreover, in [9], there is an analytical equation devised to determine the contact pressure that occurs in the process hydraulic equipment work on contact sealing surfaces.

The authors of [10] have classified the factors that determine the tightness of hydraulic cylinders, among which the main ones are considered to be the following: the seal safety factor, the value of the material layer squeezed out into the clearance, and the maximum seal contact pressure on the conjugate surface. The authors of [11] have found that the tightness of the hydraulic cylinders of automatic loaders is mainly determined by the physical and mechanical properties of the material of the self-sealing rings, including the shear modulus.

In this context, it is important to consider studies of self-sealing collar rings of hydraulic cylinders [12] that have shown a significant impact of the state of the compaction surface on the sealing process.

The results of theoretical and experimental studies of self-sealing collar rings that are used in general engineering [6–12] are very valuable in terms of quality. They help distinguish and rank the factors that influence the sealing parameters and establish the general trends and the nature of the rings' sealing ability dependence on individual factors. However, these data cannot be used to quantify the sealing ability and to construct rings of test wellhead packers as a result of a completely different configuration of the latter. This is confirmed by studies [13] that indicate that the performance and values of the pressure arising during operation significantly depend primarily on the size, shape, material and operating temperature of the seal. However, these parameters for self-sealing rings of test wellhead packers and rings used in general engineering are significantly different.

Moreover, in [6–12] there are no research findings on the simultaneous influence of the structural factors of a self-sealing ring, the intensity of the test pressure, and the time of its effect on the amount of contact pressure wherever there are conjugate surfaces.

There have been no studies of the effect of deformation and strength characteristics of self-sealing rings, including the compression modulus or the shear modulus, on the sealing performance. Practical experience has shown that a soft and supple material with a lower shear modulus can fill in the irregularities and hollows of the compaction surface faster, easier, and with less energy use. The conjugate surface of a borehole can be represented by corrosive caverns, mud, a clay crust of various thickness, and so on. This significantly increases the process of the material extrusion, which also has significant above-described flaws. Conversely, a solid material with a greater shear modulus leads to hardening of the ring. Lack of the ring flexibility has a negative impact during the initial test pressure, when installing a packer in a casing of a significant ovality, on the completeness of fitting the working surface of the ring to the conjugate surface of the casing pipe. All this greatly affects the sealing and should be taken into account.

Analysis of scientific papers [3–12] on the subject matter in question shows contemporary insufficiency of information to determine rational design parameters and operating modes of self-sealing rings of test wellhead packers in terms of a comprehensive action produced on them by force and geometrical parameters as well as material properties. This hinders their implementation in the industry and hence triggers the need for research in this area. In particular, it is scientifically and practically interesting to study a specific contact pressure distribution under conditions of different levels of the compressed state of the sealing element at different values of the test pressure, radial clearance, and tension.

3. The purpose and tasks of the study

The purpose of the present study is to obtain and analyse the dependence of the sealing ability of self-sealing rings of test borehole packers on the force factors of the testing process, the geometric characteristics of the sealing, and the physical and mechanical properties of the ring material.

The goal was achieved by solving the following tasks:

– to obtain a statistical mathematical model of the impact of the diametrical tension Δ, mm, the test pressure P, MPa, the radial clearance δ between the thrust bush and the casing pipe, mm, and the shear modulus of the material σ_{sm}, MPa on the amount of contact pressure, MPa;

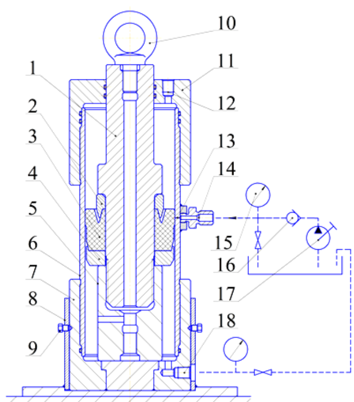
– to establish the patterns of contact pressure distribution along the length of the conjugate surface.

The solution of these problems can further improve the design of the self-sealing ring of the tested wellhead packer.

4. Materials and methods of studying contact pressure on the conjugate surfaces of a self-sealing ring

4. 1. The samples and equipment used in the experiment

To conduct an experiment for determining the contact pressure at the PJSC "Ukrnafta" (Poltava, Ukraine), a laboratory model was developed and made to help conduct the research of specimens of rings. The schematic diagram and the general look of the apparatus are shown in Fig. 2, *a, b*, respectively.



a

b

Fig. 2. A laboratory model for studying contact pressure: *a* — a schematic diagram of the laboratory model: 1 — the packer mandrel, 2 — a thrust bush, 3 — a self-sealing ring, 4 — a seat, 5 — a backnut, 6 — a pipe branch, 7 — a base cap, 8 — a thrust sleeve; 9 — fixing screws, 10 — an eyebolt, 11 — an upper cap, 12 — the inlet for the test fluid, 13 — a radial test opening, 14 — a pressure relief fitting, 15 — a test pressure gauge, 16 — a back pressure valve, 17 — a manual hydraulic pump, 18 — a drain hole; *b* — the general view of the laboratory model

The laboratory model before the study involves installation of the pre-assembled test packer of a field size: the packer mandrel (1) contains a thrust bush (2), a self-sealing ring (3) and a seat (4), which together constitute a packer seal unit and are fastened with a backnut (5). The assembled packer is pulled at tension into a pipe branch (6) (made as a casing section) that has previously been screwed with a base cap (7), and the latter, in its turn, is immobilized to prevent any possible rotation during the installation of the apparatus against a thrust sleeve (8) with fixing screws (9).

After performing these operations, the entire assembly is tightly screwed with an upper cap (11).

4. 2. A method of determining contact pressure

The method of researching contact pressure with the help of the above-described laboratory model is known as a method of Muller-Ovander (hereinafter, according to the functional features, "the method of test openings").

According to this method, contact pressure on the conjugate surface is determined by an external measuring hydraulic system that is connected to a radial opening of a small diameter (13), which is closed with the outer surface of the self-sealing ring (Fig. 2). The latter is in the inner space of the laboratory model during the test under the test pressure P. When the pressure in the external hydraulic system, which includes a test pressure gauge (15), a back pressure valve (16), and a manual hydraulic pump (17), becomes equal to the contact pressure at the point of the ring contact with the outlet of the radial opening, there will appear an aperture between the outer surface of the ring and the inner surface of the casing, and the test fluid from the measuring external hydraulic system will flow into the drain cavity to the drain hole (18). The pressure at the time of the aperture opening is considered to be equal to contact pressure with some allowance. This allowance is determined by a special calibration unit.

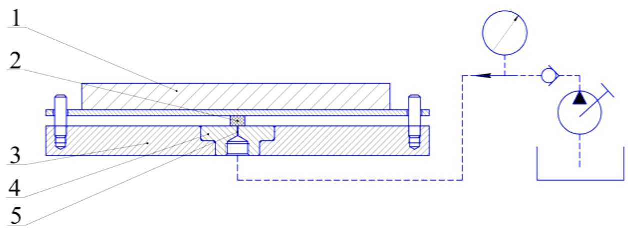
Prior to the laboratory model research (Fig. 2), calibration was performed for the test pressure gauge to record contact pressure (pos. 15 of Fig. 2) in the apparatus (Fig. 3, *a, b*). The tested rubber element had been vulcanized from the same rubber compound as the self-sealing ring of the test wellhead packer.

The calibration unit, the general view of which is shown in Fig. 3, *b*, consisted of a load (1), a rubber sample (2), a base plate (3), a changeable insert (4), and a test hole (5). The roughness of the contact surface of the changeable insert corresponded to the internal surface of the casing when tested on the laboratory model.

The essence of determining contact pressure by the calibration unit was similar to the essence of findings on the laboratory model for testing the wellhead packer. For the experiment, it was assumed that if rubber sample 2 (Fig. 3, *a*) of the contact area of 1 cm^2 was loaded with a force of 10 N, the contact pressure on the conjugate surface of the rubber element and the changeable insert had to be at 0.1 MPa. The tests on the calibration unit have helped determine a dependence of the contact pressure on the test pressure (Fig. 4), which was used in finding the contact pressure on the laboratory model.

The statistical mathematical model was obtained in the study to determine the impact of the force factors, the geometrical characteristics of the sealing, and the physical and mechanical properties of the material of the ring on its sealing ability. The experiment had been planned as full factorial, based on a Box-Hunter rotatable central composite plan for second order response surfaces [14]. The choice of the rotatable plan was predetermined by the fact that these plans make it possible to predict the value of the response function with the same variance throughout the whole factor space.

The study used rings with external diameters of 148.1...153.1 mm and a height of 75 mm, vulcanized from the rubber blend IRP-1293.



a

b

Fig. 3. A calibration unit: *a* – the schematic diagram of the unit: 1 – a load, 2 – a rubber sample, 3 – a base plate, 4 – a changeable insert and 5 – a test hole; *b* – the general view of the calibration unit

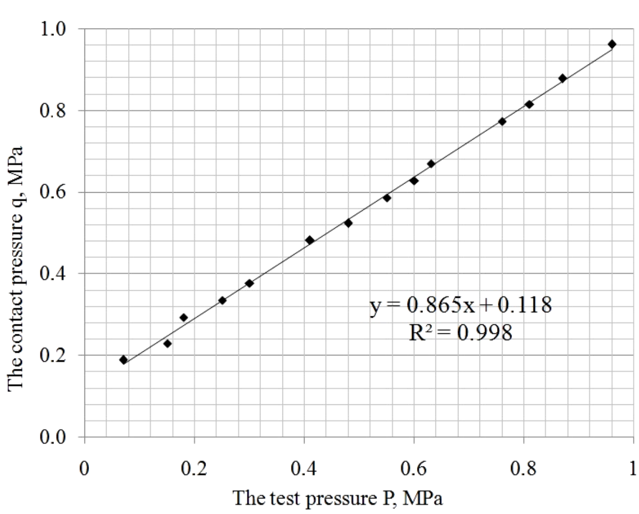


Fig. 4. A calibration dependence of the contact pressure on the test pressure

5. The research results on contact pressure

5. 1. The statistical mathematical model of the contact pressure of a self-sealing ring

When planning the experiment based on a priori information [7, 10, 11], the assumed independent factors were as follows: the diametrical tension Δ, mm, the test pressure P, MPa, the radial clearance δ between the thrust bush and the casing, mm, and the shear modulus of the material σ_{sm}, MPa. The contact pressure was assumed to be the objective function E, MPa. The core of the Box-Hunter plan of the second order was presented by the half replication 2^{4-1} ($1=X_1 \cdot X_2 \cdot X_3 \cdot X_4$). We implemented 28 experiments: 16 experiments at the main levels were supplemented with additional 8 experiments at the star points (the value of a star shoulder was 2) and 4 experiments in the centre of the plan.

The main levels of the factors' variation and the boundaries of the study scope were selected according to the results of previous experiments on the basis of a priori information (Table 1).

The scope of changes in the independent factors corresponds to the range of changes in the geometric dimensions and changes in the test conditions of the working environment.

The response function is approximated by a polynomial of the second order expressed as follows:

$$Y = b_0 + \sum_{1\le i\le k} b_i X_i + \sum_{1\le i\le k} b_{i1} X_1 X_i + \sum_{1\le i\le k} b_{ii} X_i^2, \qquad (1)$$

where k is the number of independent variables.

The processing of the experimental results and the analysis of the regression model were implemented while using the module "Experiment planning" of the statistical program Statgraphics 5.0 Plus (developed by Statpoint Technologies, Inc., USA). The regression equation (2) on the basis of the values of the factors is the following:

$$\begin{aligned} q &= 30.475 + 1.28975 \cdot X_1 + 1.99608 \cdot X_2 - \\ &-1.62917 \cdot X_3 + 1.19583 \cdot X_4 - 0.031875 \cdot X_1^2 + \\ &+0.10625 \cdot X_1 \cdot X_2 + 0.11875 \cdot X_1 \cdot X_3 + 0.00625 \cdot X_1 \cdot X_4 - \\ &-0.045375 \cdot X_2^2 - 0.11875 \cdot X_2 \cdot X_3 - 0.00625 \cdot X_2 \cdot X_4 + \\ &+0.27875 \cdot X_3^2 + 0.00625 \cdot X_3 \cdot X_4 - 0.04625 \cdot X_4^2. \end{aligned} \qquad (2)$$

The adequacy of the obtained regression model is confirmed by a high value of the coefficient of determination, R2, which amounted to 99.55 %. The significance of the coefficients of the model was determined using the P-level and presented in a standardized Pareto chart (Fig. 5, *a*).

The vertical line on the graph corresponds to the 95 % statistical significance of the coefficients.

Given the significance of the coefficients, the regression equation (3) is the following:

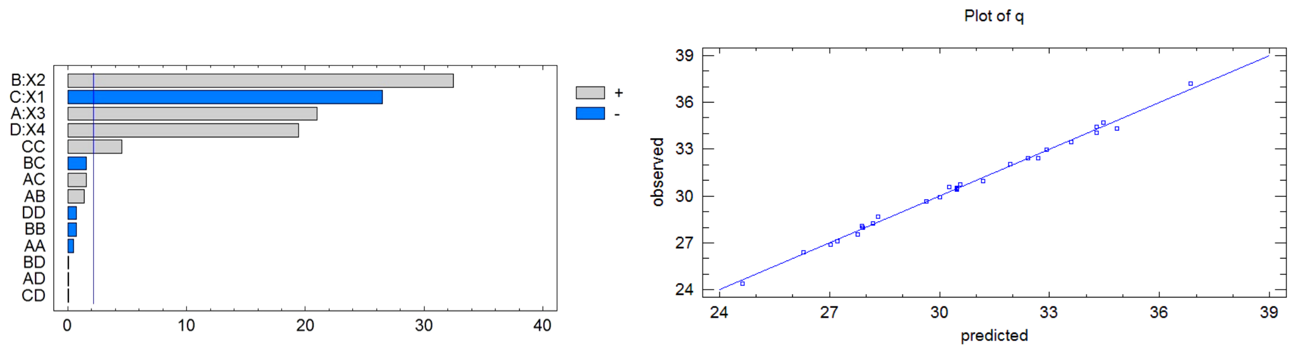
$$\begin{aligned} q &= 30.475 + 1.28975 \cdot X_1 + 1.99608 \cdot X_2 - \\ &-1.62917 \cdot X_3 + 1.19583 \cdot X_4 - 0.031875 \cdot X_1^2. \end{aligned} \qquad (3)$$

The Pareto chart shows that the most significant factor is X_2, which is the test pressure, and the next important factors are: X_1 – the diametrical tension, X_3 – the radial clearance, and X_4 – the shear modulus of the compaction material.

Table 1

The main levels, the intervals between the varying factors, and the boundaries of the study scope

The factors	Notations	Code	Unit of measure	Measurement interval	The main levels				
					−2	−1	0	+1	+2
Diametrical tension	Δ	X_1	Mm	1	1	2	3	4	5
Test pressure	P	X_2	MPa	5	10	15	20	25	30
Radial clearance	δ	X_3	mm	1	1	2	3	4	5
Shear modulus of the compacted material	σ_{sm}	X_4	MPa	10 %	2.93	2.75	2.47	1.94	1.72



a *b*

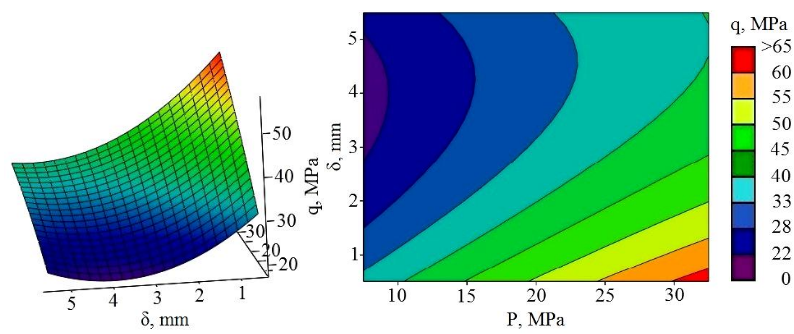
Fig. 5. The statistical estimates of the regression model: *a* — a Pareto chart; *b* — a graph of comparing the experimental (observed) and the estimated (predicted) values of the objective function

Fig. 5, *b* shows a comparison of the experimental (observed) and the estimated (predicted) values of the objective function of contact pressure.

Fig. 6, 7 show three-dimensional partial sections of the objective function and the contour curves of the surfaces displaying contact pressure dependence on the factors of influence.

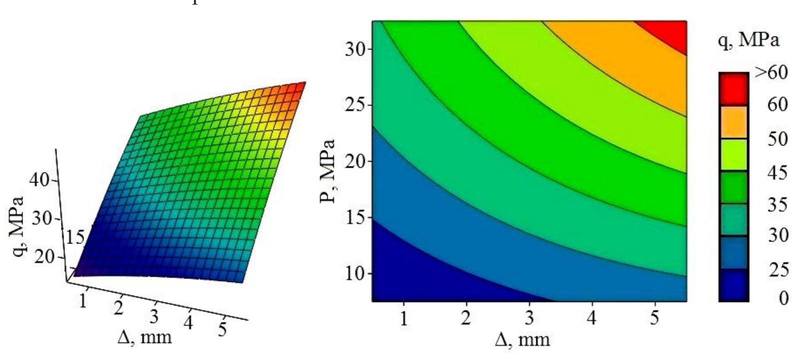
Fig. 6 shows a three-dimensional graph of contact pressure depending on the test pressure and the tension. There is an obvious dependence, which is proportional and approximately linear within the factor space.

Fig. 7 presents a three-dimensional graph of contact pressure depending on the test pressure and the radial clearance. The nature of this hypersurface is significantly different from the previous one in terms of its nonlinearity and a tendency to an extreme minimum within the factor space.



a *b*

Fig. 7. A three-dimensional hypersurface intersection of the objective function of contact pressure depending on the test pressure and the radial clearance: *a* — a three-dimensional surface; *b* — a contour curve



a *b*

Fig. 6. A three-dimensional hypersurface intersection of the objective function of contact pressure depending on the test pressure and the ring tension: *a* — a three-dimensional surface; *b* — a contour curve

5. 2. Research on contact pressure distribution along the length of the conjugate surface

Taking into account the instability of contact pressure along the length of the conjugate surface, the experimental laboratory model was used to develop a characteristic curve at a test pressure of 35 MPa (Fig. 8).

The analysis of the graphical dependence q (L) (Fig. 8) has shown a significant difference in contact pressure along the length of the conjugate surface of the ring and the casing. Contact pressure has the minimum value in the area of the ring support section.

The clearance δ with the size of ≥3 mm causes a squeezing of the ring support section out into the space area, as shown in Fig. 9.

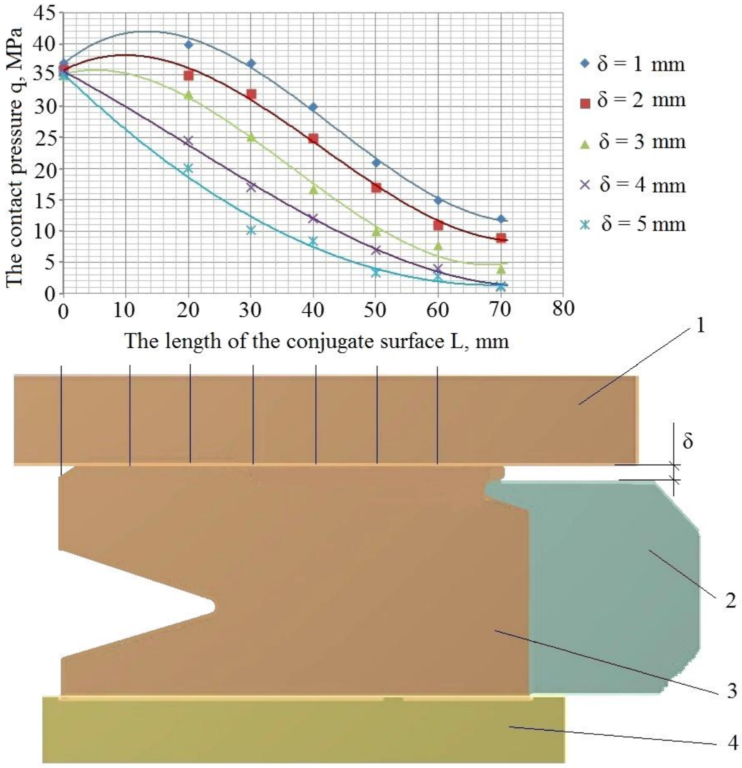


Fig. 8. A chart of the contact pressure distribution along the length of the conjugate surface based on the radial clearance at a test pressure of 35 MPa: 1 – the casing, 2 – the seat, 3 – the self-sealing ring, 4 – the packer mandrel, and δ – the radial clearance between the seat of the self-sealing ring and the casing

Fig. 9. The results of squeezing the ring support section into a 3 mm clearance after the post-experimental withdrawal of the packer from the laboratory model

The squeezing of the rubber out leads, first of all, to a significant extrusion of the material as a result of an impact of stretching forces and the contact pressure distribution along the conjugate surface, and then to a loss of the sealing ability. A critical consequence of the extrusion is destruction of the support section of the ring.

6. Discussion of the results of studying contact pressure

Our analysis of the three-dimensional hypersurface intersection of q (P, Δ) of contact pressure dependence on the test pressure and the tension shows that contact pressure increases with an increase in the diametrical size and the tension. Taking into account the research results obtained by the authors of [6], we can state that there is a considerable similarity between the results on an increase in contact pressure depending on the described factors in the ring of the tested wellhead packer and the rings of the hydrocylinder.

It is interesting to consider the three-dimensional graph of q (P, δ) of contact pressure dependence on the test pressure and the radial clearance. The radial clearance during the ring operation stands for the spatial zone into which the incompressible rubber is partially extruded under the workload (the test pressure P). Moreover, as previous studies show [7], the clearance is a major hub of tension in the ring body. It is the area where cracks can appear. Part of the material that is squeezed out into the clearance is affected by stretching forces, and at the intersection near the clearance there appears a sharp decrease in the contact pressure down to zero.

The graph q (P, δ) (Fig. 7) shows that the contact pressure with the minimum value of the radial clearance already exceeds 3 mm. If, at the same values of the radial clearance, the test pressure increases, the contact pressure increases; however, according to the regulatory requirements for the test pressure, this factor, although it directly affects the sealing ability, cannot be corrected and is to remain unchanged.

The graph (Fig. 8) of the contact pressure distribution along the length of the conjugate surface q (L) shows that contact pressure decreases from the edge of the working bite (corresponding to a mark of 0 mm on the abscissa axis) of the self-sealing ring to the supporting part (corresponding to the point of 65 mm). The local extreme maximum in the section is L=10–20 mm for δ=1–3 mm because fluid during the test partly leaks between the conjugate surfaces due to the ring trim assembly.

The curves q (L) at δ>3 mm and at δ=1–3 mm are significantly different. The intensity of the downturn of contact pressure at the radial δ>3mm increases, which is caused by an increase in the spatial area for extrusion of the sealing material.

Determination of contact pressure by the above-described method has made it possible to investigate the dependence of the sealing ability of the tested packer on a number of structural and technological factors in conditions close to the conditions of testing in the well. However, the contact pressure that is determined on the manufactured laboratory model does not allow taking into account the state of the conjugate surface of the casing pipe. In the initial stages of testing, the state of the conjugate surface is essential to ensure the tightness of the packer. A promising tendency in researching the sealing ability of self-sealing rings of borehole packers by the "method of test openings" is an additional simulation (taking into account, if applicable) of casing pipes with a different state of the conjugate surface (a weak, medium, or strong cavernosity of the surface).

7. Conclusions

1. The full factorial experimental design was based on a Box-Hunter central composite rotatable plan of the second order and was used to develop a statistical mathematical model of the impact of the diametrical tension Δ, mm, the test pressure P, MPa, the radial clearance δ between the thrust bush and the casing pipe, mm, and the shear modulus of the material σ_{sm}, MPa, on the amount of contact pressure, MPa, which is represented by a second order polynomi-

al. A Pareto chart was used to find that the most significant factor is the test pressure, whereas the next influential are the following parameters: the diametrical tension, the radial clearance, and the shear modulus of the compaction material. The developed three-dimensional graph of contact pressure dependence on the test pressure and the tension shows a dependence that is strongly directly proportional and close to the linear dependence. The three-dimensional graph of contact pressure dependence on the test pressure and the radial clearance is characterized by nonlinearity with a tendency to an extreme minimum within the factor space.

2. We have experimentally determined that contact pressure distribution along the length of the conjugate surface is characterized by a decreasing contact pressure from the edge of the working bite of the bearing part of the ring (coordinate L). The study has revealed a local extreme maximum in the area of L=10–20 mm of a clearance between the thrust bush and the supporting casing; it is δ=1–3 mm, which is because fluid during the test with a particular ring trim assembly partly leaks between the conjugate surfaces. It has been found that changes in the contact pressure along the length of the conjugate surface at the absolute values of δ>3 mm and δ=1–3 mm are significantly different. The intensity of the downturn contact pressure at the radial clearance of δ>3mm increases, which is caused by an increase in the spatial area for squeezing the sealing material. For all values of the clearance, contact pressure is minimal in the supporting area of the ring.

Thus, the research conducted on contact pressure of a self-sealing ring of a test wellhead packer has revealed an impact on the qualitative and quantitative characteristics of the sealing ability of self-sealing rings of test borehole packers made by the force factors, the geometric characteristics of the compaction, and the physical and mechanical properties of the ring material. In further studies, it is useful to consider an impact on the sealing ability of the self-sealing ring produced by the state of the compacted surface. Another still unsolved task is to determine the effect of the height of the supporting section of the ring on the distribution of contact pressure along the length of the conjugate surface.

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