Article

Optimization of the Configuration of the Power Sections of Special Small-Sized Positive Displacement Motors for Deep-Penetrating Perforation Using the Technical System "Perfobore"

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Abstract: Innovative technologies for the secondary drilling of productive reservoirs, based on the multihole drilling deeply remoted from the wellbore and with controlled trajectories, to overcome the contamination of the pay zone, and with the ability to carry out various geological and technological wellworks many times over, can significantly increase the efficiency of the development of old and marginal wells. To implement such tasks, it is necessary to use special technological drilling equipment, one such technical system (TS) is the Perfobore system, which uses a modular construction. The methodology allows to choose an optimal variant for the power sections with a high-torque, small-sized positive displacement motor PDM, previously developed by specialists at the Perfobore company. This made it possible to design universal sectional motors with diameters of 43 to 54 mm with improved characteristics compared to serial PDMs. The production of prototypes of multi-section PDMs and their successful bench and then field tests (FT), from 2018 to 2020, in the Uralopovolzhskaya and West Siberian oil and gas provinces, as part of the TS Perfobore, proved the correctness of the chosen technical strategy.

Keywords: perforating drill; secondary drilling of a pay zone; enhanced oil recovery; downhole drilling motor (PDM); multihole channels

1. Introduction

Currently, the percentage of hard-to-recover oil reserves in Russia, and across the world, is growing larger and is presently about 70% of the total. A major problem with old, low-rate wells is the lack of a high-quality, hydrodynamically perfect connection in the well–reservoir system while constructing and operating the well, caused by an external impact on the bottomhole zone, such as colmatage of the reservoir with drilling fluid filtrate or cement slurry, which are well-killing fluids. The colmatation zone can reach 8 m.

Cumulative perforation [1,2] is a major method for secondary drilling in the bottomhole formation zone. It is able to create channels that are up to 2 m long, without actually overcoming the colmatation zone. Moreover, powerful charges also result in the cracking of the cement rock, which leads to cross flows behind the casing and an increase in water cuts.

Hydro-slotted perforation [3–5] is an environmentally friendly technology of secondary drilling in the bottomhole formation zone and does not result in cracking of cement rock, but its penetration ability does not exceed 1.5 m.

At first glance, chemical methods [6] for the enhanced oil recovery, such as acid composition pumping, have a high efficiency. However, this efficiency is achieved only in formations with a uniform permeability. When the chemical composition starts to make through it is subjected to at least one layer of the enhanced permeability in the path of least resistance, substantially decreasing the overall contact zone of the acid with the formation.

Radial water jet drilling technology is a modern technology that has been developed and implemented by companies outside of Russia (RDS, PetroJet, ViperDrill, etc.) [7–12]. It allows to create long radial channels via the physical effects of erosion and cavitation. Despite the fact that this method allows to overcome the bottomhole formation zone, it has a number of significant restrictions. The channel section has an irregular shape and it is not possible to re-enter the channel; the trajectory of the channel cannot be measured nor controlled. Movement takes place towards the path of least resistance; therefore, there is a substantial risk of entering the aquiferous zone of a formation. This method works only in carbonate reservoirs and has absolutely no effect in terrigenous reservoirs, which has been proven using field tests. Additionally, the technology requires a perfect cementing quality in the sidetrack zone.

Drilling using Fishbones titanium needles [13,14] requires a costly and time-consuming procedure to remove a multi-meter section of casing before running it into the well. This only works in carbonate reservoirs and requires perfect centering in the well, otherwise the titanium needles curl around the well; this also restricts the use of the technology in open holes. Re-entry into a drilled channel is not possible.

The Perfobore technology is a new technology for the non-damaging completion of the productive formation of a well by drilling a network of branched channels with a small diameter and radius of curvature along a predicted trajectory (Figure 1). The technology is intended to enhance productive well rates and increase the injection capacity of injection wells, eliminating the cones of water–gas–oil contacts by increasing the filtration area and the system using mechanical methods for the secondary completion of the bottomhole formation zone.
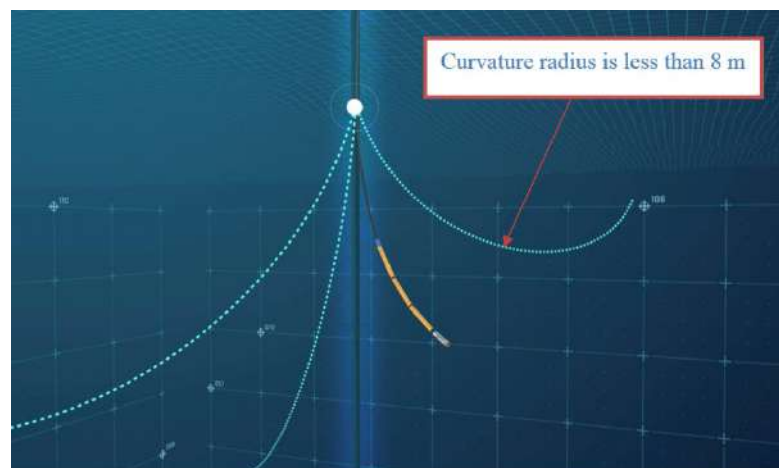

Figure 1. Network of branched channels of drilled using TS Perfobore.

The Perfobore technology, by enabling multiple entries into a drilled channel, allows to operate diverse geophysical investigations of a well, as well as acidizing or injecting diverse chemical compositions into the drilled channels through a Perfobore nozzle to stimulate the well. There is the possibility of casing the drilled channels with filters (for a terrigenous reservoir).

The areas of application of this technology include the following:

- An alternative to hydraulic fracturing. It is applicable for wells with a close location of an oil–water contact/gas–oil contact, where hydraulic fracturing is unsafe. Directional radial drilling of channels minimizes the risks of breakthrough to a water bearing bed or a gas cap.
- Involvement in the production of overlying formations: drilling a network of radial channels in multi-layer reservoirs with a high sectional structure in order to involve several isolated interlayers in the development.
- Combination with remedial cementing, which is applicable for wells with a cross flow behind the casing. After conducting an aggressive remedial cementing to isolate the cross flow behind the casing, that is, drilling channels along a predetermined trajectory to restore a link with the formation and minimize the risk of further breakthrough of the cross flow behind the casing.
- Combination with hydraulic fracturing. Drilling channels provides mining stress and sets the direction of a hydraulic fracture.
- Injection of oxidants or other reagents into the drilled channels to intensify high-viscosity oil extraction.
- Drilling channels to increase the injection capacity of wells.

  Technology applicability criterion:
- Casing diameter is from 139.7 mm to 178 mm.
- The intensity of the increase in curvature is not more than 3 degree per 10 m.
- In the operating interval, it is necessary to have a cement ring of satisfactory quality behind the production string.
- There should be no casing centralizers in the channel drilling interval.
- The frequency of holes in the previously made perforation is not more than 60 holes per a linear meter.
- The temperature at the bottom of the well is not more than 150 °C.
- The productive formation thickness is more than 3 m.

The primary functions of the Perfobore system is productive interval penetration at the completion of well construction or major repairs to the well to establish high-quality hydraulics for a perfect link between the formation and the well. The Perfobore technical system is intended for the construction of a network of branched channels with small diameters and curvature radii along a predicted trajectory The implementation of this technology has become possible through the use of specially designed small-sized equipment; for example, bore bit diameters that are from 58 to 75 mm and housing elements (body diameter, D_b) of positive displacement motors (PDM) that have diameters of 43 to 55 mm.

Moreover, the equipment is designed in such a way as to provide the drilling of channels with a constant set of inclinations. As a result of numerous bench (Figure 2) and field tests, it was found that the rate of an inclination should be from 8 to 10 degrees per meter. This is especially important in the case of the gravity method of reservoir development, in which formation fluid moves to the bottom of producing wells under the influence of its own gravity [15].

Figure 2. Bench tests of TS while drilling a channel with curvature radius of 7.7 m.

During the construction of multihole channels, significant bending moments act on the bottom-hole assembly (BHA), the magnitudes of which are comparable to the rotation moment of a small-sized PDM [16,17]. As a result of numerous analytical studies, and bench and field tests, the authors selected the required bending stiffness of the BHA and BHA design. It was also found that, for effective channel construction, a PDM must have a high rotation moment along with the bending stiffness of the assembly [18].

Since the technology uses a small-sized PDM operating at a low flow rate (up to 2 L/sec), cutting transport to the surface is impossible when using salt or fresh water. Therefore, a biopolymer solution with a low solid content is suggested as a drilling fluid for use with the Perfobore system. The recommended solution parameters are: relative weight, 1.03 g/cm^3; relative viscosity, 24 s; pH, 10.2; static shear stress, 4/6 dPa; yield point, 4 lb/100 ft^2; plastic viscosity, 8 mPa · s; and friction coefficient, 0.03.

This clayless fluid drilling achieves high and stable rheological characteristics for the hole cleaning of rock cuttings (when drilling with a low fluid flow) and minimizes wellbore damage of the bottomhole formation zone.

The composition uses calcium carbonate, specifically selected for its fractional composition, which makes it possible to create a thin and durable filter cake, which, together with its low fluid loss, minimizes the penetration of filtrate (solid phase or solution) into the bottomhole formation zone.

In the case of showings of oil–gas and water during well drilling, the density of the solution can be easily and rapidly increased at any time by adding some salt (potassium or sodium chloride), without making changes to the solution formulation or additional processing with polymers. In addition, calcium carbonate can be used for weighting.

2. Materials and Methods

2.1. Formulation of the Problem

The main elements of the PDM are the power and transmission sections (Figure 3), and the smaller their diametrical and axial dimensions are, the smaller the curvature radius that can be obtained in the constructed channel [19].

Figure 3. Photo of a two-section PDM with TS Perfobore centralizers.

When using a discontinued PDM, because of the complexity of manufacturing a D-42.9/10 type PDM, a higher rate of penetration (by 50–70%) was observed compared to when using the 2D-43.5/6.42 PDM. The reason for the higher rate of penetration while drilling using the D-42.9/10 PDM was the high rotation moment developed by the power section using the 9:10 lobe configuration [20]

The use of a high-torque drilling motor makes it possible to use it both for drilling and for intermediate casing milling (currently, the Perfobore company (Houston, USA) uses a single-section D-55 motor for milling, and a two-section 2D-43.5/6.42 PDM for drilling), which reduces the number of modules of the Perfobore technical system, significantly reducing the technological deadline for the preparation and mobilization of equipment, which increases both the technical and economic efficiencies of the process as a whole.

The algorithm for choosing the optimal version of the power section (PS) of a small-sized PDM, taking the given rotation moment and restrictions on its diametrical and axial dimensions into account, as well as the main calculated dependences of the geometric and operational parameters, is presented in Reference [21]. Initial data for calculating PDM variants are presented in Table 1.

Table 1. Initial data for calculating PDM variants.

Initial Data	Units	Value
Body diameter, Db	mm	43–55
Maximum length of working bodies (taking thread and hinge placements into account), L_{max}	mm	650
Flow rate, Q	l/s	1–2
Rotational speed, *n*	RPM	100–150
Motor torque	N·m	150
Motor torque of one engine section, M	N·m	75
Pressure drop of one engine section, P	MPa	4

2.2. Calculation of Geometric Parameters of Alternative PS Variants

Since the PDM refers to volumetric hydraulic machines, its main parameter, which determines the characteristics and the main technical indicators, is the working volume [22,23].

Based on experience in the designing of PDMs of various standard sizes for given parameters of a PDM, the nominal value of the working volume is determined through the rotation moment and the pressure drop of one engine section the hydromechanical efficiency being equal to 50%:

$$V = \frac{2\pi M}{P\eta_{hm}} = \frac{2\pi \cdot 75}{4 \cdot 0,5} \cdot 10^{-3} = 0,235 l \ .$$

After determining the required working volume, the calculation of the geometric parameters of the PS for various kinematic ratios and body diameters is carried out in the following sequence:

(1)　Determination of the contour diameter and the eccentricity of the catching;
(2)　Determination of the cross-sectional area;
(3)　Determination of the helical surface pitch;
(4)　Determination of the number of contact lines and the turn-to-turn pressure drop for the selected number of steps (it is assumed to be k = 1.5);
(5)　Determination of the length of the elastic stator line (active length of the PS).

The calculation results performed using the VINT computer program are presented in Table 2.

Table 2. Geometrical parameters of the power section with kinematic ratios of 5:6, 7:8, and 9:10 for various body diameters (V = 0.235 l; M = 75 N·m; P = 4 MPa; η_{hm} = 0.5; k =1.5).

	Body Diameter, D_b,mm	**43**	**45**	**48**	**55**
1	Contour diameter, D_c, mm	28	30	33	37
2	Eccentricity, mm				
	e 5:6	1.75	1.85	2.05	2.3
	e 7:8	1.35	1.45	1.6	1.8
	e 9:10	1.1	1.2	1.3	1.5
3	Cross-sectional area, cm²				
	s 5:6	1.25	1.42	1.73	1.92
	s 7:8	1.02	1.17	1.42	1.57
	s 9:10	0.85	0.99	1.19	1.34
4	Stage of stator, mm				
	$T_{st5:6}$	378	330	273	307
	$T_{st7:8}$	320	284	236	265
	$T_{st9:10}$	300	260	220	248
5	Average diameter of the rotor, mm				
	$d_{av5:6}$	21.0	22.6	24.8	27.9
	$d_{av\,7:8}$	22.6	24.2	26.6	29.9
	$d_{av9:10}$	23.6	25.2	27.8	31.2
6	Surface shape coefficient				
	c_s 5:6	15.0	12.2	9.2	10.35
	c_s 7:8	12.4	10.3	7.8	8.7
	c_s 9:10	11.4	9.3	7.1	7.98
7	Length of the stator line PS, mm				
	L 5:6	567	495	410	462
	L 7:8	480	426	354	398
	L 9:10	450	390	330	371
8	Number of contact lines				
	λ 5:6		4		
	λ 7:8		5		
	λ 9:10		6		

Cross-sectional profiles of the three PS variants for a body diameter of 43 mm (on an enlarged scale) are shown in Figure 4.

Option 1

Option 2

i = 5:6; D_c = 28 mm; e = 1.75 mm

i = 7:8; D_c = 28 mm; e = 1.35 mm

Option 3
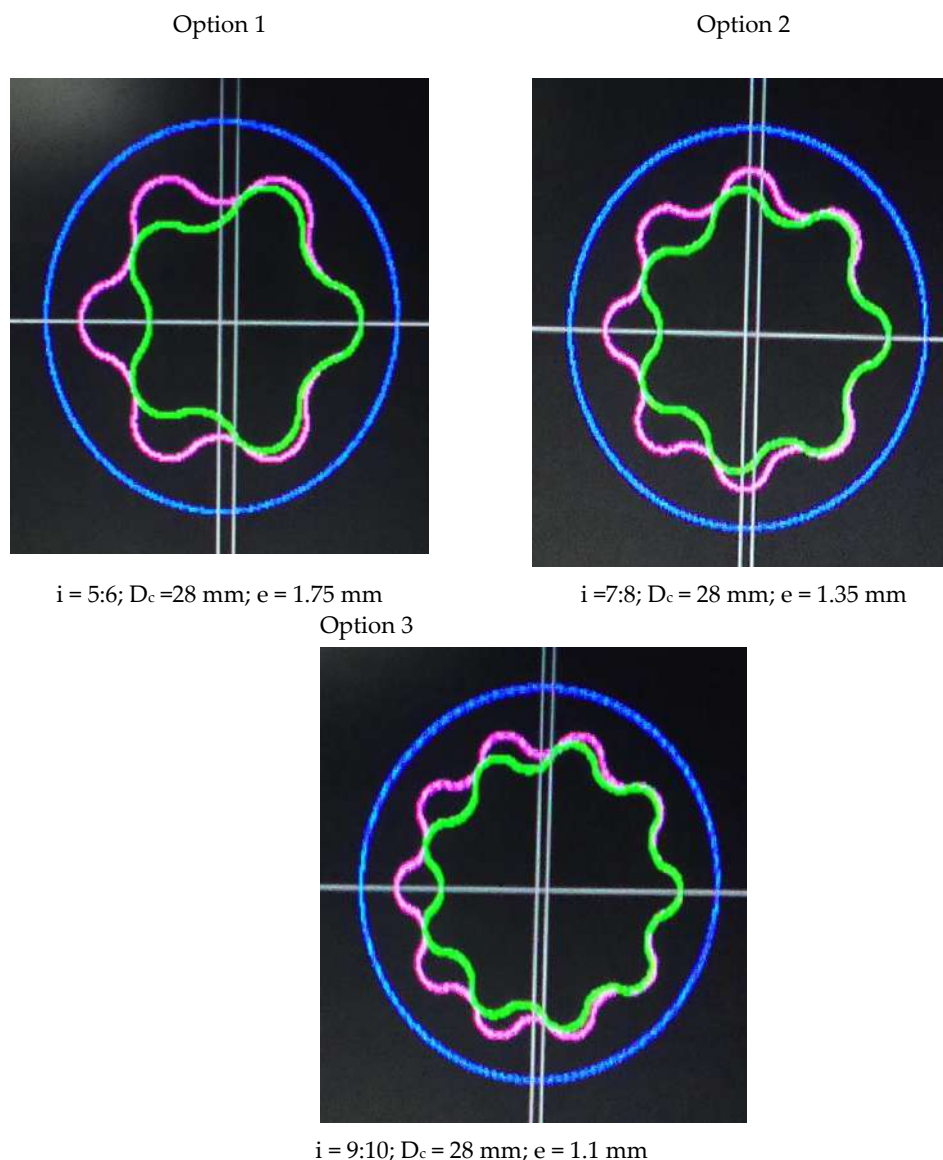

i = 9:10; D_c = 28 mm; e = 1.1 mm

Figure 4. Sections of three PS variants with different kinematic ratios.

2.3. Calculation of Operational Parameters of Alternative PS Variants

Calculation of the operational parameters of small-sized engines for the given operating conditions (M = 75 N·m; P = 4 MPa) and the selected alternative variants of the power sections (Table 2), using the example of a PDM with a body diameter of 43 mm for three kinematic ratios (5:6, 7:8 and 9:10), are presented in Table 3. When calculating the rotational speed of the output shaft, it is assumed that the volumetric efficiency (η_v) in the operating mode is 80%, and the working volume of the engine section and the displacement coefficient is refined based on the rounded-off values of the eccentricity and pitches of the PS.

Based on the performed calculations, a comparative analysis of the principal technical indicators (comparison criteria) for each variant of the PS was performed.

3. Results

3.1. Results of the Geometric Parameters Calculation of Alternative PS Variants

The analysis of the results obtained (according to Table 2) showed that an engine with a housing diameter of 55 mm is not advisable for consideration in further calculations, since the PS dimensions exceed the permissible dimensions for installing the engine into the whipstock of the Perfobore technical system when drilling with a radius of curvature of less than 8 m.

The results of calculating the geometric parameters of the PS of small-sized PDMs of various diameters, obtained under the assumption of a constancy in their working volume, make it possible to determine the degree of influence of a change in the diametric size in the required axial dimension of the PS or, in other words, the conditional "transfer function". This characterizes how much the length of a stator line PS with a certain kinematic ratio will change when the diameter changes by 1 mm.

$$f_{tr}(i) = \frac{\Delta L}{\Delta D},$$

The numerical values of function $f_{tr}(i)$ are presented in Table 4 below.

Table 3. Geometric and operational parameters of the power section of the PDM with the diametrical dimension of the sleeve being 43 mm (D_c = 28 mm; V = 0.235 l; M = 75 N·m; P = 4 MPa; Q = 1 l/s; η_{hm} = 0.5; η_v = 0.8; k = 1.5).

№	Parameters		Variant of the PS		
			5:6	7:8	9:10
1	Eccentricity, mm	e	1.75	1.35	1.1
2	Eccentricity factor	c_0	1.175	1.175	1.175
3	Tooth shape coefficient	c_e	2.175	2.175	2.175
4	Offset coefficient	ξ	−1.050	−1.030	−1.023
5	Surface shape coefficient	c_s	15.0	12.4	11.4
6	Helical line rise angle, grad	Θ	78.2	75.8	74.6
7	Average diameter of the rotor, mm	d_{av}	21.0	22.6	23.6
8	Root diameter of the rotor profile, mm	d_r	17.5	20.2	21.4
9	Stage of rotor, mm	T_r	315	280	270
10	Stage of stator, mm	T_{st}	378	320	300
11	Stator cover length, mm	L	567	480	450
12	Area of flow section, cm²	S	1.25	1.02	0.85
13	Wet perimeter, mm	Π	17.0	17.9	18.4
14	Area of contact line, cm²	$S_к$	4.1	4.5	4.8
15	Hydraulic radius, mm	R_h	7.4	5.7	4.6
16	Actual <u>displacement volume</u>, L	V	0.236	0.227	0.230
17	Length of contact line, m	L_c	298	351	423
18	Number of contact lines	Λ	4	5	6
19	Inter-turn pressure drop, MPa	P_c	1.0	0.8	0.67
20	Coefficient of unevenness of the diametrical dimensions of the profile	k_d	0.33	0.24	0.19
21	Rotary mass (length L), kg	m	1.5	1.5	1.5
22	Output speed, RPM	n	203	211	209
23	Radial hydraulic force, kN	F_h	7.1	6.9	6.8
24	Inertial force, kN	F_{in}	0.03	0.05	0.07
25	Skewing moment, N·m	M_{sc}	665	565	550
26	Axial force, kN	F_{ax}	4.1	4.6	5.0
27	Loading frequency of the stator lining, Hz	F	16.9	24.6	31.4

28	Sliding speed, m/s	v_{sl}	0.45	0.49	0.50
29	Axial velocity of the fluid, m/s	w	6.40	7.88	9.38
30	Parameter of the curvature of the profile	ϱ_{pr}/e	0.72	0.72	0.72
31	Hydraulic losses, MPa	P_h	0.009	0.014	0.024
32	Minimum contact stress, MPa	K	2.24	1.31	0.78

Table 4. Numerical values of function f_{tr} *(i)*.

	Kinematic Ratio		
	5:6	**7:8**	**9:10**
f_{tr} *(i)*, **mm/mm**	31.4	25.2	24.0

Thus, in this case, with an increase in the lobe configuration of the PS, the effect of the diametric size on the required axial dimension of the motor decreases and the difference in the stator lengths, when changing the housing diameter, will be minimal (for example, for pairs with i = 9:10, the required length when changing diameters from 43 to 48 mm changes to 120 mm).

The changes in the required lengths of the stator lines for helical pairs for the different kinematic ratios are shown in Figure 5.

Figure 5. Histogram of the changes in the required lengths of the stator lines (in mm) for different diameters and kinematic ratios (k = 1.5).

3.2. Results of the Operational Parameters Calculation of Alternative PS Variants

A distinctive feature of all PS variants of small-sized high-torque PDMs, distinguishing them from the general range of serial motors for drilling and well servicing, are significantly increased values of the helical line rise angle (more than 74 degrees) and the surface shape coefficient lobes (more than 11), which, on the one hand, allows to increase the working volume to a given value, and, on the other hand, leads to an undesirable increase in axial dimensions.

Analysis of the data in Table 3 shows that, for the given conditions, the use of PS with a kinematic ratio 5:6 is impractical, since this pair has a maximum axial dimension of L = 567 mm, which does not practically fit it into the given restrictions on the length of the section (L_{max} = 650 mm). In doing so with a one-and-a-half-pitch length of PS, it has the smallest number of contact lines (Λ = 4) and the largest turn-to-turn pressure drop (1 MPa), which limits the load capacity. In addition, the 5:6 pair is characterized by the greatest contact stress in the engagement of screw pair lobes, which will affect the durability. At

the same time, the advantages of such a pair are the minimum values of the inertial force (because of its quadratic dependence on the number of rotor entries), axial force, axial fluid velocity, and hydraulic losses in the internal channels of the PS.

With an increase in the screw pair lobe ratio of the PS, a decrease in eccentricity, area and hydraulic section radius, and the shape factor of the helical surface are observed. In this case, there is an increase in the length and area of the projections of the contact lines, the axial (loading the joint hinges) and inertial force (causing the vibration of the PDM), the loading frequency of the stator line and the axial velocity of the fluid (which for a 9:10 pair reaches 9.4 m/s). As a result, the 9:10 pair is characterized by the greatest hydraulic losses because of the high axial velocity of the fluid and the small hydraulic radius of the section (4.6 mm), additionally, there is also an increased inertial force and the stator lining loading frequency (31.4 Hz). Compared to other pairs, the 9:10 variant, from an operational point of view, has a minimal contact stress and coefficient of unevenness of the diametrical dimensions of the profile (along the projections and depressions of their lobes). The sliding speed for all variants was at approximately the same level. In addition, the mass of the rotor and the parameter of curvature of the profile hardly change.

The regularity of the change in the number of contact lines, which, all things being equal, determine the load capacity of the engine, is such that for one-and-a-half-pitch PSs, an increase in the number of entries by 2 leads to the appearance of another contact line; therefore, a 9:10 pair has two more contact lines than a 5:6 pair, which is essential in this project of the configuration of PDM.

Thus, as a prototype PS of a high-torque small-sized PDM, taking pairs of medium i = 7:8 and high i = 9:10 lobe ratios with a standard engagement geometry and a negative profile displacement coefficient is recommended. In the final choice of the variant, their principal technical indicators (geometric, hydraulic, tribological, power) should be comprehensively considered. The results of such comparison are presented in Table 5.

Table 5. Estimative comparative analysis of the technical indicators of PSs.

Technical Indicator	Variant of the PS	
	7:8	9:10
Geometric indicator	-	Preferable to eccentricity, axial dimension, the number of contact lines, turn-to-turn pressure drop and the coefficient of irregularity of diametrical dimensions profile.
Hydraulic indicator	Preferable to axial fluid velocity and hydraulic losses. [1]	
Tribological indicator	Preferable to the loading frequency of the stator line.	Preferable to length of contact lines, sliding speed, contact stress.
Power indicator	Preferable to in terms of inertial force.	
	Axial force in PS; radial hydraulic force and skewing moment both pairs under consideration are at approximately the same level. [2]	

[1] At the same time, the calculated value of hydraulic losses in the internal channels at the rate of drilling mud ($Q = 1$ L/s) is insignificant (with $Re > 100 \cdot 10^3$), which provides motivation to further use pairs with increased lobe configurations, for example 11:12; [2] however, it is necessary to note a sufficiently high level of force factors, which should be taken into account when designing joint hinges and axial bearing of the downhole assembly.

For the lower motor section of the assembly (with two shanks at the ends of the rotor), the root diameter of the rotor profile is essential, which determines the maximum possible diameter of the shank on which the connecting thread of the rotor is cut. In this respect, it is preferable to use PS with a maximum lobe configuration and minimum eccentricity.

Thus, the root diameters (d_r) of the rotor profile for pairs 7:8 and 9:10 are obtained as 20.2 and 21.4 mm, respectively. This is sufficient if the creep strength (τ_{cs}) of the rotor material is 500 MPa and the safety coefficient is 2.5. In this case, the shaft diameter required from the condition of torsional strength for M = 75 Nm is 12 mm.

Based on this, both of the selected variants, in terms of the totality of the indicators discussed above, can, in principle, be used as power sections of a PDM for the given operating parameters of the TS Perfobore. However, provided that the dominant selection criterion is the minimum axial dimension of the power section, a screw pair with a kinematic ratio of 9:10 should be recommended as the basic variant. This would provide additional and essential advantages, such as reduced eccentricity (1.1 versus 1.35 mm), minimal contact stress (0.78 versus 1.31 MPa) and a more uniform profile contour (19% versus 24%). It would also favorably affect the operability of the hinge joint, the durability of the PS and the deformation of the stator lining

Similar conclusions can be reached when choosing the optimal variant for other diametres of the PS; the geometric parameters of which are given in Table 2. The recommended variants of PS (i = 9:10) for all considered sizes are as follows:

D_b = 43 mm; D_c = 28 mm; e = 1,1 mm; T = 300 mm; L = 450 mm

D_b = 45 mm; D_c = 30 mm; e = 1,2 mm; T = 260 mm; L = 390 mm

D_b = 48 mm; D_c = 33 mm; e = 1,3 mm; T = 220 mm; L = 330 mm

Thus, for the given design conditions (V = 0.235 l; k = 1.5), the transition to the next diametric size of engine PS with a kinematic ratio of 9:10 and a negative profile displacement leads to a change in the engagement eccentricity of 0.1 mm, and in the required axial dimensions of 60 mm.

If necessary, an upgraded variant with the shortest length of power section, corresponding to 1.2 stages, can be considered. Such a design is undesirable from the point of view of the general theory of single-screw hydraulic machines [24] which will reduce the active length of the stator line (in particular, for D_b = 43 mm by 90 mm to a length of L = 360 mm, and for D_b = 48 mm by 66 mm to a very small axial dimension of the lining of L = 264 mm). However, it will also reduce the calculated number of contact lines to three (the turn-to-turn pressure drop will be 1.33 MPa), which, apparently, will require the creation of an increased overpull in the section (which can negatively affect the hydromechanical efficiency) and the use of the stiffest rubber in the manufacturing of the stator lining. For a final conclusion of the possibility of using 1,2-step pairs (or, in the limit of single) in the design of PS for small-sized engines, it is necessary to carry out bench tests and construct real characteristics of the PDM (Figure 6).
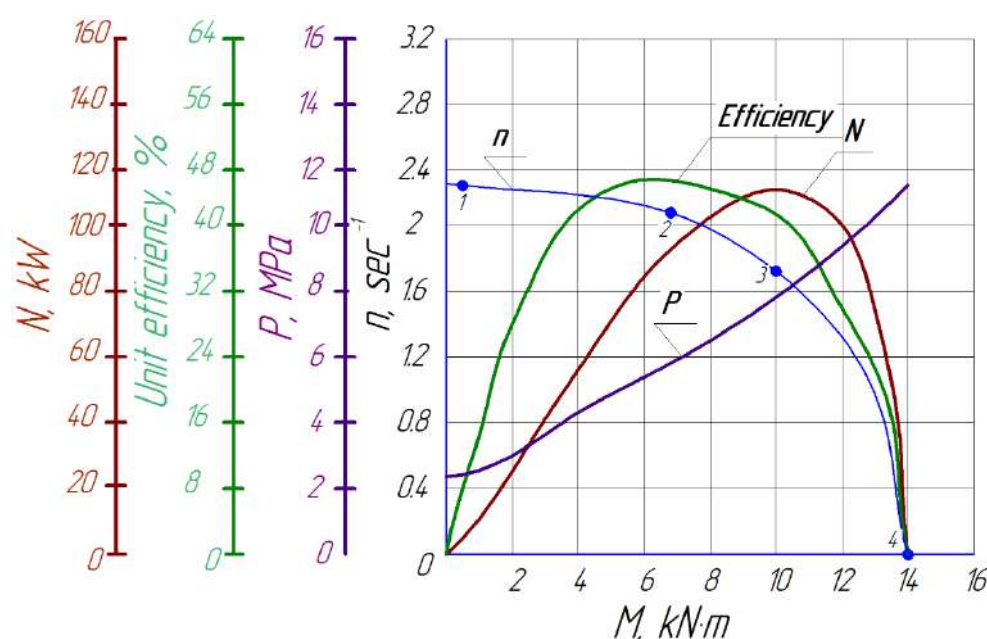
Figure 6. Typical characteristics and points of characteristic modes of small-sized PDM.

Another little-studied issue that the authors are going to consider experimentally, after carrying out the FI, in order to further increase the rotation moment of the PDM of a limited axial dimension, is the determination of the boundaries of stability and load bearing capacity of an engine (or the permissible differential pressure Δp) for various flow rates at modes close to braking (to the right of the point of optimal mode 2, Figure 6) when the pressure drop exceeds the nominal value of 4 MPa, and the volumetric efficiency and engine speed have reduced values because of an increase in leakage in the PS.

4. Discussion

In 2019, the Perfobore company conducted a series of field trials (FT) of special assemblies with centering elements placed on a developed small-sized sectional PDM in the Arlanskoye oil field of LLC Bashneft-Dobycha. One of their test objectives was to verify compliance with the calculated (planned) and the actual trajectories. As part of the FT, two different geophysical instruments were lowered into the drilled channels with the help of TS to eliminate the errors associated with the possibly of incorrect operation of the inclinometers. One inclinometer was a small-sized magnetometric inclinometer, "KVARTS-36", and the second one was a small-sized gyroscopic inclinometer "TWIN GYRO". Both inclinometers were autonomous.

After the measurements, the obtained data were interpreted and the trajectories of the drilled channels were constructed in comparison with the planned ones (Figures 7 and 8). The curvature radii of the drilled channels were less than 8 m and the deviations of the drilled trajectories from the planned ones were 3–5%.
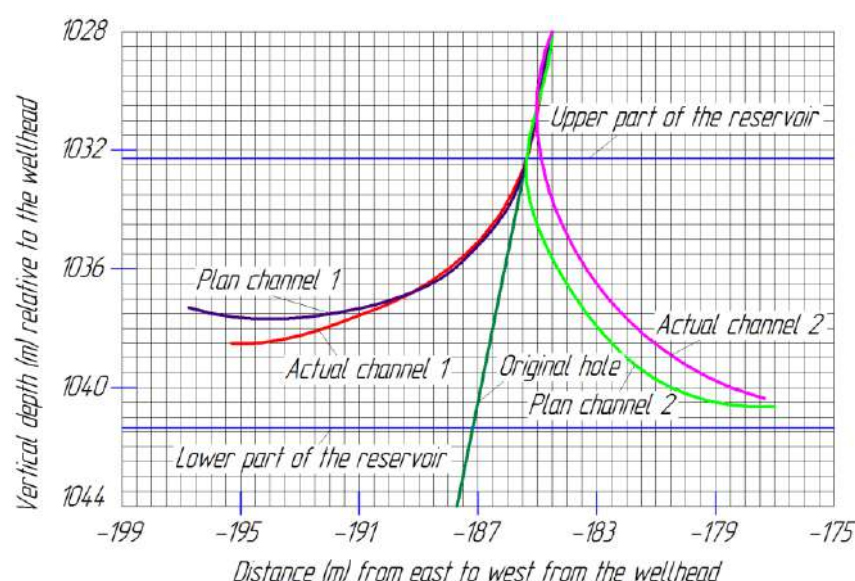
Figure 7. Drilled channel trajectories (side view) based on data from the gyroscope, "TWIN GYRO", (No. 1 in red) and the inclinometer, "KVARTS-36" (No. 2 in purple).
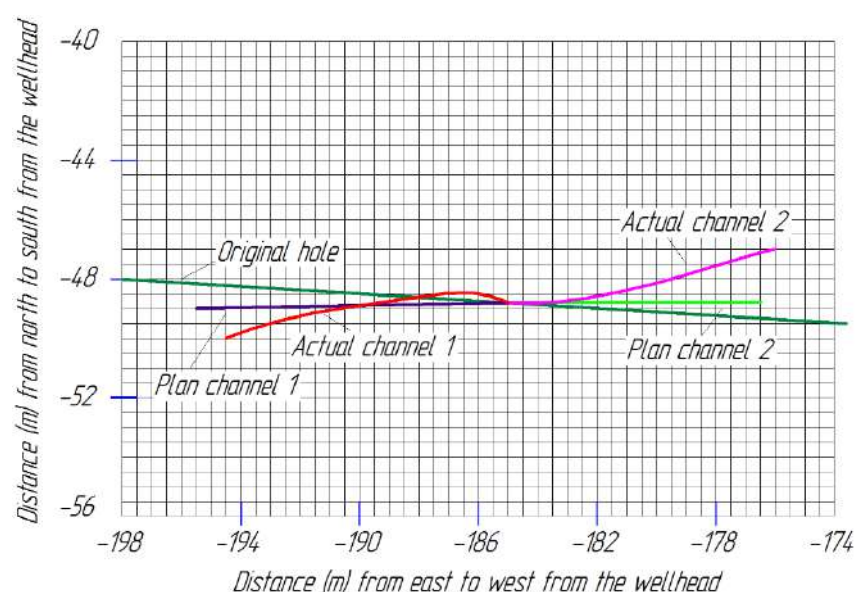

Figure 8. Drilled channel trajectories (top view) based on data from the gyroscope, "TWIN GYRO" (No. 1 in red), and the inclinometer, "KVARTS-36" (No. 2 in purple).

5. Conclusions

In the long term, it seems expedient to further search for technical and technological solutions aimed at increasing the hydromechanical efficiency of a screw pair (in the calculations it is taken at a standard level for multi-threaded screw pair of 50%), which in the case of an increase in this efficiency, which is responsible for mechanical and hydraulic losses in PS of up to 60%, will reduce the length of a motor section by another 10%. As such, for housing elements with a diameter of 43 mm, it is possible to obtain a workable axial dimension of the stator lining within 375 mm.

Based on the developed methodology for choosing the optimal variant of the power section of a downhole drilling motor, a rational configuration of a universal downhole drilling motor was selected for drilling a network of branched channels using the TS Perfobore. It has been established that the use of PS with a kinematic ratio of 5:6 does not

meet the basic technical requirements needed in terms of geometric, tribological indicators. A screw pair with a kinematic ratio of 9:10 is recommended as the optimal version of a small-sized PDM. The PDM with a diameter of 48 mm with a kinematic ratio of 9:10 was adopted for implementation, since its manufacture (according to a special technical assignment) is economically justified. This engine with installed centralizers allows drilling with a radius of curvature of less than 8 m, which meets the objectives of the technology (completion of thin layers). Moreover, the choice of the PDM with a diameter of 48 mm originated from the possibility of using a bit with a larger diameter than that used when drilling the PDM with a diameter of 43 mm, which has a positive effect on the effective filtration area of the drilled channel.

A PDM with a diameter of 43 mm and a kinematic ratio of 9:10 is expected to be produced in the future, since such a PDM will reduce the value of the radius of curvature and, as a result, expand the field of application of the technology. However, from a technological point of view, the manufacturing of such a PDM is a more laborious process.

The use of the developed universal downhole drilling motor will allow milling and drilling of channels using one drilling tool for a round trip, which optimizes equipment manufacturing costs, reduces the final cost of the service for the customer, and expands the scope of application of the developed innovative technology of perforating drilling, both in high-rate and low-rate wells, including fields that are currently considered to have hard-to-recover reserves.

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