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Methodology for calculating technical efficiency of power sections in small-sized screw downhole motors for the «Perfobur» system

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With an increase in the share of old and low-yield wells and for the efficient exploitation of fields, it is necessary to include low-capacity formations into production. There are many wells where sidetracking and hydraulic fracturing are difficult due to the close proximity of the gas cap and underlying water caused by geological and technological reasons, and the use of existing secondary drilling-in technologies is not effective due to the extensive colmatated zone or annular circulation. Relevance of radial drilling technologies is growing, which allows drilling-in of the formation with a network of extended channels to establish high-quality hydraulic communication between the formation and the well without affecting the permeability of the formation.

In contrast to radial drilling technologies using hydraulic washing, technical system (TS) «Perfobur» uses small-sized screw downhole motors (SDM) and rock cutting tools for channel construction. For efficient milling of production casing and destruction of rock, the hydraulic downhole motor must have high torque, and for the possibility of drilling with a high rate of angle gain, it must have short power section. Existing Russian and foreign SDM have limited number of standard sizes and do not meet the requirements specified for the development of the downhole module of TS «Perfobur».

The paper discusses the development of universal small-sized sectional screw downhole motors for milling casing strings and drilling a network of branched channels of super-small diameter and radius of curvature as a part of the TS «Perfobur». Methodology proposed in the article for selecting optimal configuration of the SDM power sections allows constructing small-sized sectional downhole motor that meets the technical requirements and has improved characteristics compared to standard SDM.

Key words: Perforation bit; secondary reservoir drilling-in; enhanced oil recovery; deep perforation drilling; screw downhole motor

Introduction. Growth of the country's oil and gas industry is largely associated with the development and implementation of innovative technologies in the field of drilling and repair of oil and gas wells. Such a technological structure is the technical system of borehole and surface equipment proposed by «Perfobur» LLC for drilling multilateral wells (with super-small diameter shafts and curvature radius) along the predicted trajectory from a cut-out window in the casing [1, 3, 4, 7-9, 16, 17, 19].

The upgraded design of the TS «Perfobur» is manufactured in a modular design for ease of assembly at the wellhead area and increased operational efficiency. The main elements of the TS are: rigid structure (pipe pusher) connected at the top with an overflow valve module, and at the bottom with a guiding device connected by means of a hydraulic pusher (operating in damper-oscillator modes) and a flexible pipe assembly with a small-sized (non-standard) sectional SDM, and drilling bit (milling cutter at window cutting). A special whipstock and an anchor module with an orienting funnel are connected from below to the pipe frame (fig.1).

Modular design version of «Perfobur» allows composing the lower module in the form of technical structures regulated by numerous oriented whipstocks placed sequentially even in horizontal wellbores, with the possibility of stepwise extraction and reinstallation, including with corrected orientation. The technology allows creation of skeleton-like channels branched with a predicted oriented trajectory in both open (carbonate) and cased wells during secondary drilling-in of productive formations of oil and gas-condensate fields.

Autonomous inclinometer module and a special inkjet device for dosing the drilling fluid flow rate at the inlet of the SDM and efficient transport of cuttings are located above the SDM. The assembly is lowered into the well with technological tubing (TT), flexible tubing (FT) or drilling pipes.

Main elements of the TS «Perfobur» are the working bodies of the SDM, which create the necessary torque to drive the milling cutters that cut windows in the casing string, or bits, drilling the rock along the super-small radius of the channel curvature (fig.2).

As the working bodies (WB) of the motor, a multi-thread gerotor mechanism (rotor-stator pair) with a cycloidal tooth profile (fig.3) is used, which is effectively used in Russian and foreign practice of drilling and repair of the wells [1, 2, 19].

Limited diametric and axial dimensions of the screw pair due to the general strict requirements to the bottomhole assembly of the TS «Perfobur», are causing the correction and refinement of the adopted approaches in the design of screw pairs, which leads to the use of non-standard technical solutions that contribute to achieving the specified characteristics of the SDM and are associated with the need to obtain high torques considering noted limitations [6, 13].

Statement of the problem. Let us consider the problem of increasing the quality indicators of the SDM efficiency. For a volumetric screw hydraulic machine, the working process of which has been studied in detail [1, 5, 14], the characteristic of the rotational speed n and torque M for a given flow rate of the working fluid Q, determined according to the conditions for flushing the channel in the well and taking into account the characteristics of the mud pumps, is directly related to the working volume V:
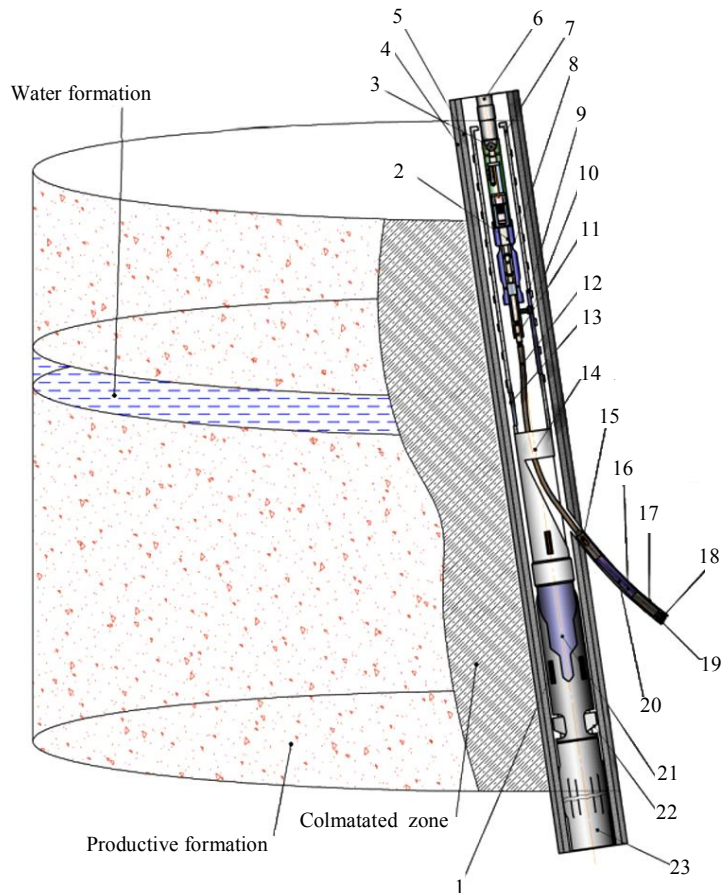

Fig.1. Downhole modules of TS «Perfobur»

1 – hole for the hook; 2 – filter; 3 – valve joint; 4 – cement stone; 5 – casing string; 6 – tubing string / FT string; 7 – pipe frame; 8 – pusher; 9 – directing groove; 10 – spline inset; 11 – hydraulic loader; 12 – flexible pipe; 13 – discharge groove; 14 – whipstock; 15 – autonomous inclinometer; 16 – SDM; 17 – centralizer; 18 – drilling bit / milling cutter; 19 – perforation channel; 20 – perforation bit of BHA; 21 – orienting device; 22 – clasp; 23 – anchor (profile pipe)
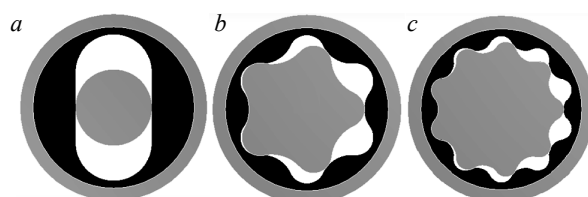

Fig.2. TS «Perfobur» assembly in horizontal well

Fig.3. Cross sections of SDM working bodies with different kinematic ratio – 1: 2 (*a*); 5:6 (*b*); 9:10 (*c*)

$$n = \frac{Q}{V}\eta_o ; \quad M = \frac{PV}{2\pi}\eta_{gm} , \qquad (1)$$

where η_o – volumetric efficiency; η_{gm} – hydromechanical efficiency; P – pressure drop.

In this regard, an increase in the torque M of the screw pair in the general case can be achieved in three ways:

• increase in working volume

$$V = z_2 ST,$$

where z_2 – lobe; S – live cross-section area; T – pitch of a screw surface.

• increase in pressure drop P;

• reduction of hydromechanical losses (increase of hydromechanical efficiency η_{gm}).

Distinctive feature of the small-sized SDM WB is that with a decrease in the contour diameter, the live cross-section area S sharply decreases, therefore, to save the working volume, a significant increase in the pitch of the screw surface T is required, which contradicts the need to have a significant number of WB pitches to create high pressure drop. Possible way to overcome this problem, based on an increase in the lobe z_2 of a screw pair, as follows from the general theory of single-screw hydraulic machines, developed by scientists and specialists [9], turns out to be effective only to a certain limit, since with a number of lobes more than 10, working volume curve is flattened, so the only solution to this problem is associated with the attempt to maximize the live area S and reduce the pitch of the WB.

Another distinctive feature of small-sized SDM is an increase in their rotation speed in comparison with medium- and large-sized motors (with a diameter of 127 mm or more) [1, 2, 5, 6]. Theoretically, this is explained by the fact that, at other things being equal, the working volume of the SDM is proportional to the cubed diameter D of the WB, and the annular cross-sectional area F_{cs} of the well to the squared D. As a result, the dependence of the rotational speed on geometric parameters and fluid flow rate can be represented as an inversely proportional function of the diameter

$$n = \frac{Q}{V}\eta_o = \frac{v_{cs}F_{cs}}{V}\eta_o = C\frac{v_{cs}}{D} ,$$

where C – constant of SDM with specific size; v_{cs} – upstream velocity in the annular space of the well.

To overcome this pattern and reduce the rotational speed while reducing the diameter of the SDM, in some cases WB with an increased pitch (screw surface shape factor of more than 8) are used, however, this leads to the lengthening of the screw pair, complication of the stator manufacturing technology and a decrease in the pitch number of WB, which reduces the load ability of the hydraulic machine.

Specified technical characteristics of the SDM for TS «Perfobur»:

Frame diameter, mm…………………...…………….. 47-49
Maximum length of working bodies
(considering threads and hinge placement) L, mm…… 650
Flow rate Q, l/s………………………...…………1-2
Rotation frequency n, rpm…………….…………… 100-150
Output shaft torque M, N·m……………….…...……150
Torque of one pair M, N·m…………….…………75
Pressure drop of one pair P, MPa………….……….. 4

Comparative characteristics of small-sized SDM

Manufacturer, model	Flow rate Q, l/s	Moment of force M, N·m	Rotation frequency n_x, min^{-1}	Pressure drop P, MPa	Lobe i	Pitch number k	WB length L_{act}, мм	Inter-turn pressure drop P_k, MPa
VNIIBT-BI:								
D43.5/6.42	0.2-0.5	30-60	120-294	2.5-5.4[*]	5:6	4.2	760	0.35
D43.3/4.50	1-2	30-60	138-336	2.0-5.2[*]	3:4	5	1000	0.40
D43.5/6.36	1-2	80-150	282-564	4.5-7.0[*]	5:6	3.6	1300	0.50
Radius-Servis:								
RS043N518	0.8-2.5	110	160-520	3.1[*]	5:6	3.3	1500	0.36
PNMR:								
D-43.5/6.10	0.8-2.5	110	179-611	3.7[*]	5:6	–	970	–
InBurTeh:								
DP-43.5/6.36	1-2	60-110	282-564	3-6	5:6	3.6	1300	0.38
NOV:								
1-11/16"5/6.5,0 CT	1.6-2.8	165(248)	323-582	5(7.5)[*]	5:6	5	–	0.3(0.4)
Lilin:								
5LZ43-7,0L-4-192	0.8-1.6	56	435-870	3.2	5:6	4	–	0.17

[*] Differential pressure drop

Currently, leading Russian and foreign manufacturers of SDM are mass-producing a limited number of standard small-sized motors with a diameter of 43 mm. The table shows the main technical characteristics of standard small-sized SDM (D = 43 mm) produced by Russian (VNIIBT-BI, Radius-Servis, PNMR, InBurTeh), western (NOV) and Chinese (Lilin, JM) enterprises [14, 15, 18].

Analysis of the table allows concluding that none of the standard small-sized motors of Russian and foreign production fully meets the requirements specified for the development of the downhole module TS «Perfobur» due to either insufficient torque or excessive length of screw working bodies.

Methodology. Let us choose the optimal ranges of dimensionless geometric parameters of the working bodies. The WB geometry of a single-rotor hydraulic machine with cycloidal engagement for a given contour diameter D_k is completely characterized by the following dimensionless parameters [1, 5]: kinematic ratio $i = z_2/z_1$; coefficient of eccentricity $c_o = r/e$; tooth shape coefficient $c_e = r_c/e$; displacement coefficient $\xi = \Delta x_1/e$; allowance coefficient $c_\delta = \delta/d_{av}$; surface shape coefficient $c_T = t/d_{av}$; pitch number $k = L/T$, where z_1, z_2 is the number of teeth of the stator and rotor; r is the radius of the rolling circle; e – eccentricity; r_c is the equidistant radius; Δx_1 is the displacement of the initial contour of the cycloidal rail; δ – diametric allowance; t, d_{av} – pitch and average diameter of the rotor surface.

At present, designing of the WB for screw hydraulic machines considers concept, according to which only two out of seven dimensionless coefficients mentioned above are strictly regulated – the coefficients of eccentricity and tooth shape, the values of which according to OST 39-164-84 are c_o = 1,175; c_e = 2,175.

Choice of other factors depends on the operating mode of the screw mechanism and design requirements. Allowance coefficient c_δ is assigned based on the reaching of the required load capacity of the hydraulic machine, and the screw surface shape coefficient c_T – according to the minimum length of the pump's contact lines or according to the start-up conditions c_T = 5-7 – for the SDM [1, 11, 12]. Screw surface shape coefficient c_T along with the displacement coefficient ξ is a free variable and is determined after calculating the pitches of screw surfaces of the WB necessary to provide a given working volume (for a given kinematic ratio and live cross-section area). The pitch number of the stator screw surface k, which determines the axial dimension of the WB, is assigned depending on the torque or the required durability of the screw pair, taking into account the permissible inter-turn pressure drop. This approach was also adopted in the development of the design methodology of WB for the universal high-torque small-sized SDM for use in the TS «Perfobur».

Modern approaches to selecting the properties of the elastomer plates indicate the possibility of increasing the load capacity of a screw hydraulic machine. Thus, for example, in relation to SDM, NOV in its catalogs demonstrates the possibility of a significant increase in torque (by 50 %) when switching from standard rubber to a special elastomer such as PowerPLUS for any diametric dimensions. Therefore, the selection of the stator plate elastomer along with the optimization of the geometric parameters of the WB is also a promising direction for improving the characteristics of small-sized SDM.

Selection of the optimal parameters for the WB is the most significant step in the design of screw hydraulic machines. During optimization, in general, the following comparison criteria are used [1, 10]:

• geometric – contour diameter D_k, kinematic ratio i, eccentricity e, working volume V, length L (pitch number k) of WB, area S and perimeter L_g of live cross-section, projection area of contact lines S_k, hydraulic radius of section $R_g = S/L_g$, equivalent radius of curvature ρ_{eq}, teeth height $h = 2e$, number of contact lines;

• energy – length of the contact lines L_k, inter-turn pressure drop P_k; hydromechanical efficiency η_{gm}; hydraulic losses P_g;

• durability – contact stress K in the teeth engagement, sliding speed v_{sk}, axial fluid velocity w, loading frequency of the elastic stator plate f, inertial force F_{in} on the rotor due to the planetary nature of its movement; skew moment M_s;

1.102 Max
1.001
0.8996
0.7983
0.6969
0.5956
0.4943
0.3929
0.2916
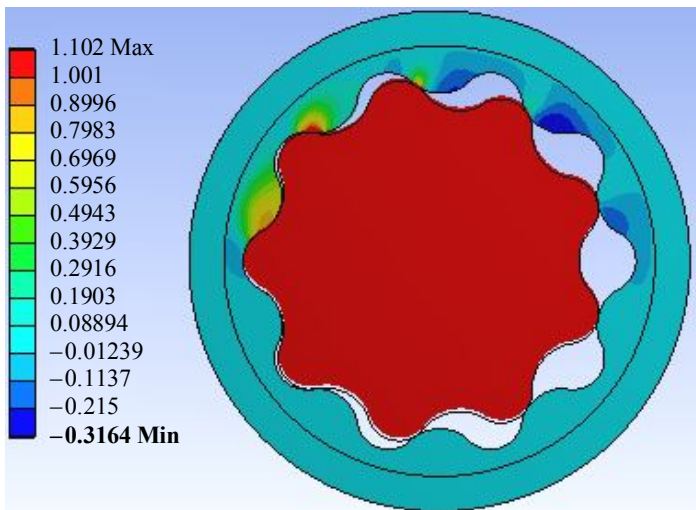0.1903
0.08894
−0.01239
−0.1137
−0.215
−0.3164 Min

Fig.4. Isolines of rotor and stator points' displacement in specified sections of working bodies with kinematic ratio 9:10
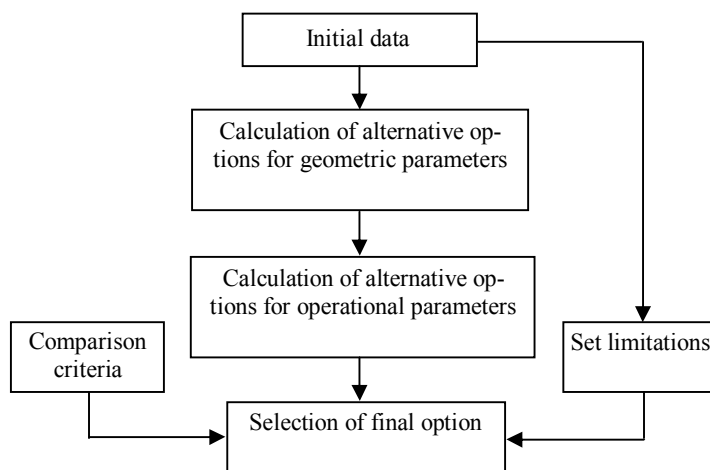

Fig.5. Algorithm of selecting optimal option for working bodies of the screw section

• technological – unevenness coefficient of the profile diametrical dimensions (over the protrusions and troughs) $c_{\Delta h}$, relative geometric coefficient L/D_k, which determines the ratio between the axial and diametrical dimensions of the WB.

An accurate determination of the stress-strain state of the SDM WB and calculation of contact stresses and deformations of various teeth in the stator plating for given loads is carried out on the basis of the ANSYS software package using plane or spatial modeling of the WB screw surfaces. Figure 4 shows a computer calculation example of the displacements of the WB rotor and stator cross-sections.

Discussion. After analyzing all the criteria that determine the geometric, operational, and technological parameters of the SDM, the final decision is made on the selection of the optimal structure of the WB, the algorithm of which is shown in fig.5. Then follows the development of design and technological documentation for the manufacture of the rotor and stator.

Comprehensive analysis of the geometric and operational comparison criteria using the proposed algorithm made it possible to formulate the principles underlying the methodology for selecting the optimal WB structure of the universal

high-torque small-sized SDM for the TS «Perfobur»:

• full utilization of the useful cross-sectional area (diametric dimension) of the SDM in order to obtain the maximum possible contour (along the stator teeth cavities) diameter of the WB;

• use of multi-lobe screw pairs with a kinematic ratio in the interval of 7:8-9:10;

• profiling of WB from a cycloidal rail with a negative displacement corresponding

Fig.6. Lineup of bottomhole assemblies TS «Perfobur»

to a corrected profile with a coefficient $\xi = -1$, which ensures maximum live cross-section area;

• selection of the active length of the elastic plate based on the one and a half-step stator ($k = 1.5$), which allows maintaining a relatively high number of contact lines (at least 5) separating the input and output of the hydraulic machine, with a minimum axial dimension;

• application of stator plate elastomers with special physical and mechanical properties, characterized by increased hardness of the elastomer in order to maintain high load capacity while reducing the number of contact lines and increasing inter-turn pressure drop relative to standard WB of mass-produced motors.

Depending on the capacity of the reservoir, «Perfobur» has developed a model range of devices with different radii of curvature $R = 3.5$-12 m and dimensions of special SDM (fig.6).

Conclusion. Developed methodology for selecting optimal WB option for a universal high-torque small-sized SDM for the TS «Perfobur» allows construction of sectional motors in the size range of 43-54 mm with improved characteristics compared to standard SDM. Production of multisectional SDM prototypes and their successful bench and field trials in 2018-2019 in the Ural-Volga and West Siberian oil and gas provinces, as part of the TS «Perfobur», proved the chosen technological strategy to be correct.
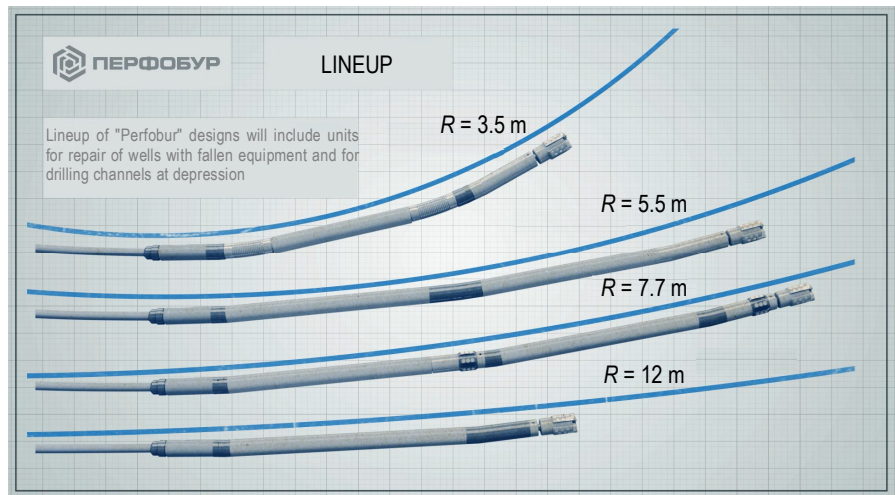
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