12. Vaickelionis, G. Production of Expanded Clay Pellets by Using Non-selfbloating Clay, Lakes Sapropel and Glycerol [Text] / G. Vaickelionis, A. Kantautas, D. Vaiciukyniene // Materials Science. – 2011. – Vol. 17, Issue 3. – P. 314–321. doi: 10.5755/j01.ms.17.3.600
13. Cheilytko, A. A. Experimental studies of thermal properties of porous particulate material according to the different modes of heat treatment [Text] / A. A. Cheilytko // Eastern-European Journal of Enterprise Technologies. – 2009. – Vol. 5, Issue 6 (41). – P. 4–7.
14. Cheilytko, A. A. Vspuchivanie poristogo kremnezemistogo materiala [Text] / A. A. Cheilytko, A. M. Pavlenko. – Saarbrucken, Deutschland: LAP LAMBERT Academic Publishing, 2013. – 130 p.

UDC 628.243.2
DOI: 10.15587/1729-4061.2017.99032

DEVELOPMENT OF THE MODEL OF PETROLEUM WELL BOREABILITY WITH PDC BORE BITS FOR UZEN OILFIELD (THE REPUBLIC OF KAZAKHSTAN)

B. Fedorov
Doctor of Technical Sciences, Professor*
B. Ratov
Doctor of Technical Sciences, Associate Professor*
A. Sharauova
Postgraduate student*
*Department of Technology and techniques of drilling wells
Kazakh National Research Technical University after K. I. Satpayev
Satpaev str., 22a, Almaty, Republic of Kazakhstan, 050013

Для буріння свердловин на великому нафтогазовому родовищі Узень (Казахстан) замість шарошечних доліт з великим ефектом застосовуються долота PDC. Дані про показники роботи інструментів оброблені методами статистики. Створено відповідну модель буримості. Модель містить три параметри: початкову швидкість, темп зниження швидкості і показник ступеня, в яку зводиться час буріння. Модель дозволяє прогнозувати і оптимізувати роботу долота PDC

Ключові слова: свердловина, модель буримості, долото PDC, знос, порівняльна оцінка, шарошечні долота

Для бурения скважин на крупном нефтегазовом месторождении Узень (Казахстан) взамен шарошечных долот с большим эффектом применяются долота PDC. Данные о показателях работы инструментов обработаны методами статистики. Создана соответствующая модель буримости. Модель содержит три параметра: начальную скорость, темп снижения скорости и показатель степени, в которую возводится время бурения. Модель позволяет прогнозировать и оптимизировать работу долота PDC

Ключевые слова: скважина, модель буримости, долото PDC, износ, сравнительная оценка, шарошечные долота

1. Introduction

The boreability model represents an analytical relationship reflecting the process of interaction between the rock-cutting tool and the borehole bottom in time.

A well-established boreability model usually takes into account the main factors influencing well deepening and enables prediction of the bit functioning, well formation at the lowest specific operating costs and optimization of the drilling process.

The numerous boreability models available at present are designed for roller bits. Rotary-percussion method of hole-bottom destruction, design complexity and versatility of use of the mentioned bits should be noted. Comparatively recent PDC bits differ from the roller bits by the rotary method of hole-bottom destruction by a microcutting mode, design simplicity and extremely high durability in soft and partially medium hardness rocks as well as the work of diamond-set hard metal alloy cutting structure by the principle of self-sharpening. Because of the widespread of PDC bit introduction into practice, it is urgent to solve the problem of making the boreability model with an account of the design features of the rock-cutting tool.

2. Literature review and problem statement

There are a number of models of boreability describing the process of bit-to-hole bottom interaction.

The best-known model of boreability is as follows [1, 2]:

$$\vartheta(t)=\vartheta_0\exp(-\beta t), \quad (1)$$

where $\vartheta(t)$ is the boring speed at the time point t; ϑ_0 is initial boring speed (formally at t=0); β is the constant depending on the parameters of the boring technique, the bit design and the rock properties.

A distinctive feature of this model is its simplicity and a small amount (only two) of identification constants. At the same time, the model is only suitable for the boring process, which proceeds with an intensity decaying in time.

The most complete analytic study of $\vartheta(t)$ function was presented in work [3]. The following differential equation was proposed for this function:

$$\frac{dv}{dt}+\varphi\vartheta^k=0, \quad (2)$$

where φ and k are the equation parameters depending on the wear resistance of the tooling, abrasiveness of rocks and the bit operation mode.

The form of solution of equation (2) is determined by the value of the exponent k. For k=0, the relation v(t) is linear:

$$V=V_N-\varphi\cdot t. \quad (3)$$

Solution of equation (2) for k>0 (with the exception of k=1) takes the form:

$$V=\frac{V_o}{\sqrt[k-1]{(1+(k-1)V_N{}^{k-1}\varphi\cdot t}}, \quad (4)$$

and for k=1

$$V=V_N\exp(-\varphi\cdot t), \quad (5)$$

That is, it coincides with formula (1).

Solution of equation (2) for k<0 takes the form:

$$V=\sqrt[1-k]{\left(V_o^{1-k}-(1-k)\varphi\cdot t\right)}. \quad (6)$$

In work [4], it was proposed to use approximate power formula to describe dependence v(t):

$$V=\frac{V_o}{(1+t)^{\beta}}. \quad (7)$$

In the presence of dependence of v on t, it is not difficult to calculate penetration per bit as well:

$$H=\int_0^T V(t)\cdot dt, \quad (8)$$

where T is the bit durability (the bit working time at the hole bottom).

Graphical dependences computed from formulas (3)–(6) are given in works [1, 3] in which the relative mechanical boring speed equal to the ratio ϑ/ϑ_0 is plotted on the ordinate. The value of velocity at the end of boring was assumed to be equal to $\vartheta=0.5\vartheta_N$. This position follows from the recommendations of work [5], that is, it is assumed that the roller bit has exhausted its tool life when the mechanical boring speed is halved. Such worn bit should be taken to the surface and replaced with a new one.

Analysis of the graphs of functions (4)–(6) given in work [1] shows that the shape of the curves depends on k parameter. Thus, dependence $\vartheta(t)$ is a monotonous decreasing concave curve for k>0, and a monotonely decreasing convex curve for k<0. With increasing by modulus of the k parameter, the curvature of the dependences increases. It should also be noted that the dependence $\vartheta(t)$ calculated by formula (4) practically coincides with the approximate dependence $\vartheta(t)$ calculated by formula (7).

Analyzing the obtained dependences (2)–(6), one can conclude that the above formulas correctly reflect the behavior features of the rock-breaking tool when boring various rocks. This primarily applies to roller bits of the first and second classes (concave curves $\vartheta(t)$ are for the first class bits and the convex dependences are for the second class bits). At the same time, the mentioned formulas and the conclusion on the bit rise time when the boring speed drops by half compared to the initial speed are only valid for the roller bits. The practice of boring with bits based on other principles of hole bottom destruction, in particular PDC bits, indicates existence of other patterns of «bit – rock» interaction.

For further optimization of boring processes, formula (4) is also used in work [6] in the following form:

$$\vartheta(t)=\vartheta_0\left[1+k(n-1)\vartheta_0^{n-1}\right]^{\frac{1}{n-1}}, \quad (9)$$

where k is the wear coefficient; n is the characteristic of the curve shape $\upsilon(t)$ (convex or concave shape).

In formula (9), like in the previously mentioned formulas (4) and (6), there are three identification parameters: ϑ_0, k, n, that is, the initial boring speed ϑ_0, wear parameter k, and the parameter n characterizing the rate of wear (growing or slowing down process).

In principle, these relationships can be used to describe the impact on the hole bottom not only for the roller bits but also rock cutting tools of a cutting type (naturally, the identification parameters will be quantitatively different).

Authors of work [7] propose to change the average value of the mechanical bit velocity in the boring process by the form of this formula:

$$\vartheta_N=\vartheta_{m>}-\varphi h, \quad (10)$$

where ϑ_m is the current value of the mechanical velocity; ϑ_{mo} is the initial mechanical velocity; φ is the tangent of the straight line slope to the h axis; h is the current headway value in the middle of the interval of the average mechanical boring velocity.

The initial mechanical velocity ϑ_{mo}, which is present in formula (10), is determined by the following expression:

$$\vartheta_{mo}=\frac{a\omega^{\beta}P^{\alpha}}{1+(bP)^k}, \quad (11)$$

where ω is the angular velocity, s^{-1}; P is axial load, kN; α, b, β, k, a are constant coefficients depending on the bit design and the properties of the destroyed rock.

Formula (10) does not inspire confidence, just because its members in the right side have different physical dimensionality.

As regards formula (11), in order to calculate the maximum (often rational) boring velocity, it is necessary to carry out experimental and production tests to determine values of the five coefficients.

Finally, the following mathematical model was proposed in work [8] for characterizing the boring process:

$$\vartheta(t)=\vartheta_o-\Delta\vartheta t^m, \qquad (12)$$

where $\vartheta(t)$ is the current (during the time t of the bit's stay at the borehole bottom) boring velocity; ϑ_0 is initial mechanical velocity over a measured period of time, $\Delta\vartheta$ is the rate of decrease in the mechanical velocity of penetration in the initial period, m/hr; m is the exponent.

Dependences $\vartheta(t)$ for different values of the exponent m take the forms shown in Fig. 1.

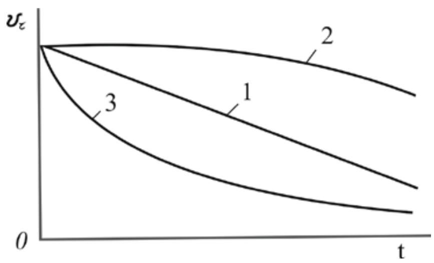

Fig. 1. Forms of dependences $\vartheta(t)$ for different values of exponent m: 1 — constant intensity of curvature (m—1); 2 — increasing intensity of curvature (m>1); 3 — decreasing intensity of curvature (m<1)

Penetration per run h is found by integrating the function (12):

$$h=\vartheta_o t-\Delta\vartheta\frac{t^{m+1}}{m+1}. \qquad (13)$$

Comparing the model (12) with other models, which were considered, its advantages can be noted:

– model (12) has wide universality, contains time factor t and includes three identification constants: ϑ_0, $\Delta\vartheta$, m;

– the model (12) is quite simple in comparison with other models and implicitly takes into account the influence of parameters of the drilling technique and the design of the rock cutting tool on intensity of the borehole bottom destruction;

– using concrete examples, the developed procedure for identification of the boring model was given and satisfactory results consistent with practice were obtained.

However, the developed procedure was designed to describe the boring process based on the impact of a cone bit on the borehole bottom and does not take into account the features of boring with highly durable drag bits.

Foreign references are mainly devoted to a complication of the model of drillability by taking into account new factors affecting the boring process. Work [9] considers modeling of vibrational oscillations of the drill string affecting the process of destruction of the borehole bottom. It should be noted that this factor has little effect on boring intensity when boring shallow wells with downhole motors. This is due to the lack of rotation of the drill string and a significant decay of oscillation intensity.

The authors of another work [10] note that transition from static models of the boring processes to the dynamic models is currently underway. The latter additionally take into account factors such as drill string vibrations, temperature stresses and multiphase boring fluids.

This complication of models leads to the use of new controlled functions and rise in boring costs. This is justified in construction of deep wells by rotary method in difficult drilling conditions when the effect of the mentioned additional factors on the boring process grows.

The general tendency of foreign publications is complication of the boring process model by inclusion of new factors in the corresponding equations. Influence of these factors is taken into account by new controlled functions that enable automation of the process of boring deep wells in difficult conditions.

With the advent of PDC diamond-set hard metal alloy drilling bits [1, 2], the parameters of the boring process in soft and partly medium-hardness non-abrasive rocks have changed significantly. Resistance (the service life of the drilling bit cutting structure) has reached 5.000 m of bored wells, the design of the rock cutting tool has become much simpler, reliability of its work has increased in comparison with the cone bits. An opportunity has appeared to drill wells by a rational technique with the use of screw downhole motors. This, in turn, enabled reduction of loading of the drill strings and increase in service life of the latter.

It is in such favorable conditions for the use of PDC bits that wells are being put into operation at a large Uzen (Kazakhstan) oil and gas field. The well depths measure 1,200–1,400 m, the geological section is represented by clays, non-abrasive limestones, marls, sandstones related to the category of soft and partially medium hardness rocks by their boreability. The oil well design is as follows. Slip box diameter: 324 mm (interval 0–30 m); conductor diameter: 243 mm (interval: 0–220 m); flow string: 168 mm; (interval: 0 to the design depth). Boring for the slip box was carried out with a roller bit III 393.7 mm (Russia); boring for the conductor was done with a 295.3 mm bit and the hole for the flow string bored with a 220.7 mm PDC bit (Kazakhstan). In boring for the slip box and the conductor, torque was transmitted to the bit thru the rotor and the VZD-172 screw downhole motor (Russia) having 6,000–6,500 NM torque on the shaft at a rotation frequency of 3–3.7 s^{-1} was used in the flow string boring. Rational boring mode parameters have been determined. For example, when boring for the flow string, the parameters were as follows. Axial load: 40–50 kN, bit rotation velocity: 1.5–2 s^{-1}, mud flow rate: 28–32 l/s.

Favorable geological section and small well depths made it possible to drill the longest interval for the flow strings occupying 85 % of the total well metreage in four, sometimes in five wells.

Hundreds of wells were drilled in the field with PDC bits but no model for well formation with this rock-cutting tool has been developed so far. In other words, the quantitative regularity of the mechanical boring velocity variation with the bit wear was not established. This regularity would enable forecast and optimization of further operational costs per meter of well boring.

Analysis of available domestic and foreign scientific and technical literature on boring (textbooks, monographs, articles) shows that there is no documents concerning development of a boreability model for PDC bits taking into account the specifics of their work at the borehole bottom. Such features include: exceptionally high durability in soft and medium hardness non-abrasive rocks, the feature of the diamond-set hard metal alloy drilling bits working in a self-sharpening mode and design simplicity in comparison with the roller bits.

3. Objective and tasks of the study

This study objective was to develop a model of boring with the PDC bits at their repeated use in a homogeneous geological section.

The main tasks of the study were as follows:

– timekeeping observation of boring performance with 220.7 mm PDC bits for flow strings and the degree of tool wear;

– grouping of data on productivity of boring with PDC bits, rejecting «suspicious data» and the grouped data processing;

– determination of the degree of wear of the PDC bit after boring of each concrete interval for the flow strings;

– plotting graphical and analytical dependence of boring productivity with the PDC bit on the time of its stay at the borehole bottom;

– calculation of identification parameters and compilation of the boreability model, analysis of the results obtained.

4. Materials and methods of studying mathematical statistics

To solve the first task, timekeeping observations of the process of boring the hole for the flow string with 220.7 mm PDC bits. Each new bit was marked by notching, connected to the drill rod and lowered into the well. In the process of boring, the initial boring rate was registered, then the same parameter was measured every 8 hours of bit operation. The bit pulling out time was registered after boring the whole interval for the flow string and the bit surface was inspected to determine wear of the working elements.

Then the second notch marking was made on the bit which was used repeatedly for the flow string boring in another well and the same parameters were registered (boring velocity versus time, lowering-lifting operations time, the bit surface visual inspection). Then the third mark (notch) was made. The bit was again used bore the flow string in the third well with registering abovementioned parameters. And finally after pulling the bit, the last, fourth mark was notched, the tool was again lowered into the well for the flow string boring in the fourth well with registering the change in the boring velocity depending on the time, lowering-lifting operations term and the degree of bit wear.

In order to solve the second problem, the obtained data on the results of the flow string boring with PDC bits were divided into 4 groups. The principle of data partitioning into groups was the number of boring flow string intervals, which were precollared with PDC bits. As a result, four groups of the bit performance data depending on the time spent at the borehole bottom were obtained.

The first group included data on the change in the boring velocity at the flow string boring interval depending on time, with a new, unused earlier bit. The second group contained data on the mentioned functional linkage for the bits that were previously used in boring the flow string interval in the wells of the first group. The third group contained data of boring productivity depending on time with the bits, earlier used in wells of the first and second groups. Finally, the fouth group represented a set of values of the boring velocity altering depending on time with the bits previously used to drill the flow string interval in the wells of the first, second and third groups.

To solve the third task, the «suspicious data» were rejected by the «three sigma» criterion. Such rejected data included: errors of the experimenter who measured increase in boring velocity in the second group of wells in comparison with the first group, failure of several working elements of the bit because of an excessive axial load, complications, which caused the necessity of the bit lift.

In total, of the 127 experimental wells, data for 11 wells were rejected and data for 116 wells were left for analysis.

The number of wells in each group from which data were taken for further studies is given in Table 1. The changes in boring velocity ϑ when boring the flow string interval and the boring time t in each group of wells are given there, too.

To establish the tightness of relationship between time t and boring velocity ϑ, the correlation ratio τ [11] for each group of wells was determined (Table 1). The value of τ for all groups of wells was close to 1 which indicated a connection between t and ϑ close and the functional one.

The process of boring the flow string interval with PDC bit consecutively in well groups results in a gradual wear and shortening of the tool service life. Perform now an approximate evaluation of the process of bit wear. When boring with a new bit (the first group of wells), the mechanical velocity fell from V_{max}=19 m/hr to V_{min}=14 m/hr (Table 1). The main cause of such process is decrease in durability because of the bit wear, A_{u1}, which can be roughly determined from the equation:

$$A_{u1}=\left(1-\frac{V_{min1}}{V_{max1}}\right)100\,\%. \tag{14}$$

Table 1

Data of statistical processing of the boring velocity with the PDC bits by well groups

Well group No.	Number of wells in a group	Change in boring velocity, m/hr	Weighted-mean boring velocity V_m, m/hr	Interval boring time t, hr	Correlation ratio τ
1	21	19–14	17.0	64.6	0.93
2	60	14–12	13.05	78.1	0.92
3	20	12–8	10.5	97.6	0.94
4	15	8–6.5	6.98	133.6	0.94

Substitute the data from Table 1 in (14) and obtain:

A_{u1}=(1–14/19) 100 %=26.3 %.

Decrease in durability in the second group of wells will take into account bit wear in the first group

$A_{u2}=A_{u1}$+(1–12/14) 100=26.3+14.3=40.6 %.

In the third group, taking into account the previous wear, it gives:

$$A_{u3}=A_{u1}+A_{u2}+(1-8/12)\,100=40.6+33.4=74\ \%.$$

At the final stage, when boring the flow string interval in the fourth group of wells, the bit wear will reach a value equal to:

$$A_{u4}=A_{u1}+A_{u2}+A_{u3}=$$
$$=26.3+14.3+33.4+(1-6.5/8)\,100\ \%=94\ \%.$$

Thus, service life of the PDC bit after boring the interval in the fourth well has almost been exhausted. The following metreage has been bored with one new bit:

$$(1340-220)\cdot 4=4480\ \text{m},$$

which was generally confirmed by the boring practice for oil and gas wells in the Uzen field.

The obtained data on boring velocity in each group enabled establishment of the dependence of the boring velocity on the time of the bit stay at the borehole bottom. The well boring time in each group under the number n is determined by:

$$t_n = S_{int} / V_{awds}, \tag{15}$$

where S_{int} is the length of the bored interval in each group of wells $S_{int}=1120$ m; V_{cpn} is the weighted mean boring velocity corresponding to the interval S_{int} in the group under the number n ($n=1, 2, 3, 4$). The boring time for the flow string interval depending on the degree of bit wear is given in Table 1 for each group of wells

Calculations according to (15) show that the main well interval (220–1380 m) for the flow string was bored with a new PDC bit in 64.6 hours (2.7 days). When boring the second well, the same interval was bored in 78 hours (3.25 days) with a total bit wear of 40.6 %. The same interval during boring in the third well was completed in 97.6 hours (4.1 days) with a total bit wear of 74 %. Finally, during boring of the interval in the fourth well, 133.6 hours (5.57 days) were spent, and the total wear of the tool was 94 %. The remaining 6 % of the bit life, judging by the steepness of the graph of function $\vartheta f(t)$ at the final stage of interval boring (220–1380 m) in the fourth well drastically goes down. This indicates accelerated wear of the remaining bit structure life literally equal to 10–15 hours of operation.

Taking into account the data on the boring velocity of the PDC bits and the corresponding time the bit spent at the borehole bottom, the $V_M(t)$ dependence shown in Fig. 2 was obtained.

As it follows from analysis of function $\vartheta=f(t)$ graph, the upper section BA of the curve is concave and the lower section AC is convex.

The obtained dependences $\vartheta(t)$ (curve 1 in Fig. 2) are well approximated by the parabola equation of the following form:

The BA curve:

$$\vartheta = 1{,}02\cdot 10^{-4} t^2 - 7{,}04\cdot 10^{-2} t + 19{,}2;$$
$$(0<t<170). \tag{16}$$

The AC curve:

$$\vartheta = -8{,}17\cdot 10^{-4} t^2 + 10^{-2}\cdot 2{,}402t + 8{,}278;$$
$$(170<t<360). \tag{17}$$

Search now for the model of boreability in the form of equation (12). As the constants of model identification, initial velocity, the rate of decrease in the mechanical boring velocity ΔV and exponent m to which the boring time t is raised will serve. Since curve 1 has an inflection point (point A in Fig. 2), the boreability model will be represented by two equations.

The constants ΔV and m were determined by the method described in [9] for the conditions considered are as follows:

– for the upper section BA of the curve $\vartheta=f(t)$:

$$\Delta V=0{,}107\ \text{m/hr};\ m=0{,}83;\ V_0=18\ \text{m/hr};$$

– for the lower section AS of the curve $\theta=\vartheta(t)$:

$$\Delta V=0.037\ \text{m/hr};\ m=0.87;\ V_0=10.4\ \text{m/hr}.$$

Thus, the boreability models look like this:

$$\vartheta_t = 10{,}4 - 0{,}107t^{0{,}83}, \tag{18}$$

where t varies in the range of $0 \le t \le 170$ hr (the boring time in the wells of the first and second groups).

$$\vartheta_t = 10{,}4 - 0{,}037t^{0{,}87}, \tag{19}$$

where t varies within the interval $170 \le t \le 370$ hr, i. e. the boring time of the main interval in the wells of the third and fourth groups.

It follows from (18) and (19) that the rate of reduction of mechanical velocity ΔV when boring with a new bit the flow string interval in the first group of wells is much higher. Obviously, this is due to the configuration of the diamond-set hard metal alloy plates reinforcing the PDC bit.

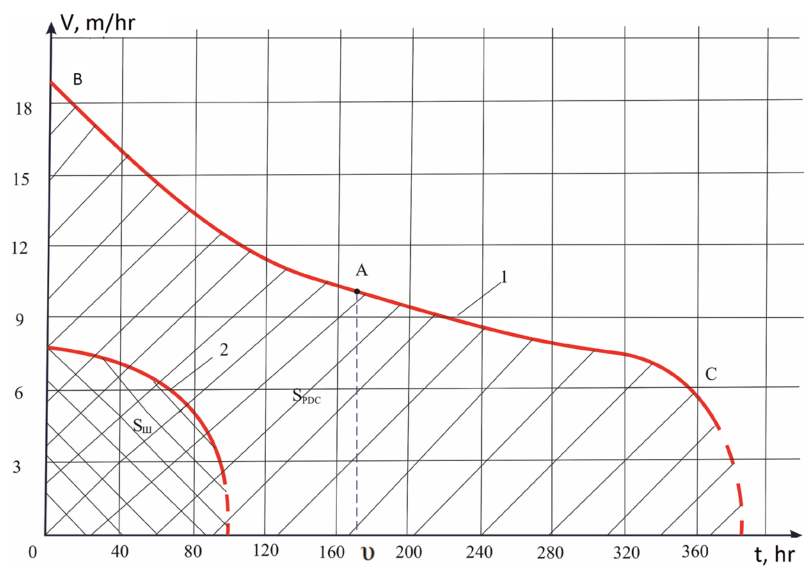

Fig. 2. Dependence of boring velocity of PDC bit (Kazakhstan) and the III-215.9 NAT roller bit (People's Republic of China) on the time t of tool work at the borehole bottom: curve 1 is for PDC bits; curve 2 is for roller bits

Prior to the use of PDC bits, boring at the Uzen deposit was carried out by a rotary method. Well formation for the flow string was carried out using III-215.9 NAT roller bit of Chinese production with the following parameters of working conditions: axial bit load: 160–180 kN; bit rotation velocity: 90 rpm; boring mud consumption: 28 l/s.

Analysis of design documentation (flow sheets, geotechnical conditions) has enabled establishment of the following boring indicators of the roller bits used:

– initial mechanical boring velocity: $\vartheta_0=8$ m/hr;

– average boring velocity: $\vartheta_{op}=6.5$ m/s;

– average penetration per bit: $S_{rb}=630$ m;

– working time of the bit at the borehole bottom: 95–100 hrs.

Processing of the results using the same technique which was used for the PDC bits has made it possible to determine the following boreability model for III-215.9 HAT (PRC) bits:

$$\vartheta_t = 8 - 0{,}018\,t^{1{,}3}\ \text{m/hr}. \quad (20)$$

Fig. 2 shows curve 2 graphically depicting the boreability model (20) for roller bits.

5. Discussion of the results obtained in the studies of the established boreability model

The established boreability model enabled prediction of the PDC bit durability if the time of its work at the borehole bottom or boring velocity at the considered moment of time is known. For example (Fig. 2), if the bit was already 180 hours at the borehole bottom, its remaining service life (its durability in hours) is characterized by the ACDE area. The corresponding initial boring velocity is 10.5 m/hr.

The studies which were carried out to determine the boreability model are applicable for a homogeneous geological section of rocks having approximately equal physical and mechanical properties. Such homogeneous section is typical for the Uzen field (Kazakhstan).

Further studies will be aimed at establishing boreability models for PDC bits in a heterogeneous geological section. This will extend the field of effective application of the models when using the mentioned bits. The above studies continue the well-known works on simulation of boring with roller bits and take into account features of boring with diamond-set hard metal alloy boring bits.

It is common knowledge that the PDC diamond-set hard metal alloy drilling bits work at the borehole bottom by the self-sharpening principle, that is, the rock is broken with the diamond exposure as a result of advanced wear of the carbide pad. Nevertheless, the obtained result indicates a decrease in the bit boring velocity with the time of work at the borehole bottom (curve 1 in Fig. 2): a significant drop initially, then a prolonged monotonous, slow decrease in boring velocity, and a sharp drop in productivity and complete wear of the bit armament in the final period. This change in velocity is probably due to the circular shape of the diamond-carbide working elements. In the initial boring period, a short C chord (Fig. 3) is formed on the diamond layer which causes the minimum area of contact of each round working element with the borehole bottom. This predetermines greater depth of penetration of each element into the rock under the action of axial load and, therefore, higher boring velocity.

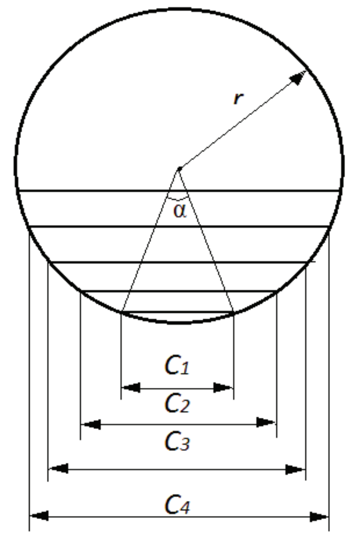

Fig. 3. Change in the length of C chord on the diamond plate in the course of wear out

As the round working element wears, the C chord size grows according to the following formula:

$$C = 2r\sin\frac{\alpha}{2}, \quad (21)$$

where r is the plate radius and α is the central angle.

As a result, the area of contact between the diamond layer and the borehole bottom increases. The area of contact of the carbide base of the working element increases as well with its advanced wear out and exposure of the diamond cutter. All this leads to a slowdown of the boring velocity, initially being significant due to a rapid growth of the C chord and then more gradually higher which results in a monotonous, long slowdown of velocity. The sharp drop in velocity at the final stage of boring (a complete wear of the cutting armament) is explained by the fact that after the wear-out of the round diamond-carbide element to half the diameter, the contact area with the borehole bottom is composed of the contact area of the diamond and carbide plate and a part of the bit body area. The sharply increased contact area of the bit with the borehole bottom causes a sharp drop in velocity and exhaustion of the bit service life.

6. Conclusions

1. A procedure of timekeeping observation of the boring process with PDC bits has been developed taking into account their repeated use in several wells before the final end of their service life. The characteristic feature of this procedure consists in monitoring of performance and degree of wear of the new bit while sequentially boring the first, second, third and fourth flow string intervals.

2. A procedure was developed for grouping boring performance with PDC bits according to the principle of the number of intervals (wells) that were drilled with this tool. The characteristic feature of this procedure was that

the first group included data on the boring performance for the flow string with new, previously unused PDC bits; the second group included the same data obtained in the flow string boring with bits that were used earlier in the first group of wells; the third group contained the data obtained when boring the flow string interval with the bits previously used in the wells of the first and second groups, etc., until the PDC bits were completely worn out. Then, «suspicious data» not characteristic of the boring process at the deposit were deleted from the data grouped according to this principle.

3. A close functional relationship between the change in the boring velocity and the time of the bit operation has been established.

4. A quantitative estimation of the degree of wear of the PDC bit by the difference in boring velocities at the beginning and the end of the time interval of well deepening to the initial boring velocity of this interval has been established. The total wear of the PDC bit was equal to the sum of bit wears that it undergone in a sequential boring of the flow string interval. In this case, when boring an interval of 220 to 1340 m in four wells, the total wear of the bit was 94 %.

5. The dependence of the boring velocity on the time of the bit work at the borehole bottom was established. The dependence represented two conjugate parabolas where the parabola has a concave shape in the initial period and a convex shape in the final period of use.

6. The following identification parameters were obtained for the boring process at the Uzen field:

– for the first operation period ($0<t<170$ hrs) with a new, unused PDC bit: $\Delta\vartheta=0.107$ m/s, $m=0.83$;

– for the second final period (170 hrs$<t<$370 hrs) of the bit operation: $\Delta\vartheta=0.037$ m/hr, $m=0.87$.

The established boreability model is characterized by two equations: $\vartheta_t=10{,}4-0{,}107t^{0{,}83}$, $\vartheta_t=10{,}4-0{,}037t^{0{,}87}$.

References

1. Popov, A. N. Tekhnologiya bureniya neftyanyh i gazovyh skvazhin [Text] / A. N. Popov, A. I. Spivak et. al. – Moscow: Nedra, 2007. – 512 p.
2. Kalinin, A. G. Stroitel'stvo neftegazovyh skvazhin [Text] / A. G. Kalinin, A. S. Oganov et. al. – Moscow: RTUNG im. Gubkina, 2013. – 580 p.
3. Badalov, R. A. Opredelenie mekhanicheskij skorosti prohodki v zavisimosti ot rezhimnyh parametrov bureniya [Text] / R. A. Badalov // Izv. Vuzov. Neft' i gaz. – 1960. – Issue 1. – P. 52–58.
4. Ejgeles, R. M. Raschet i optimizaciya processov bureniya [Text] / R. M. Ejgeles, R. V. Strekalova. – Moscow: Nedra, 1977. – 200 p.
5. Sinev, S. V. Modeli processa bureniya [Text] / S. V. Sinev // Neftegazovoe delo. – 2009. – Vol. 2. – Available at: http://ogbus.ru/authors/Sinev/Sinev_1.pdf
6. Sitnikov, N. B. Matematicheskaya model' processa bureniya glubokih geologorazvedochnyh skvazhin [Text] / N. B. Sitnikov, V. V. Makarov // Izv. vuzov. Gornyj zhurnal. – 1992. – Issue 1. – P. 62–68.
7. Kalinin, A. G. Razvedochnoe burenie [Text] / A. G. Kalinin, O. V. Oshkordin, V. M. Piterskij, N. V. Solov'ev. – Moscow: Nedra, 2000. – 748 p.
8. Levickij, A. Z. Issledovanie dannyh geologo-tekhnicheskogo kontrolya dlya optimizacii bureniya [Text] / A. Z. Levickij. – Moscow: VNIIOEHNG, 1987. – P. 14–31.
9. Alkaragoolee, M. A hybrid model for a drilling process for hydrocarbon well-boring operations [Text] / M. Alkaragoolee, K. Ebrahimi, R. Whalley // Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics. – 2017. – P. 146441931769785. doi: 10.1177/1464419317697854
10. Florence, F. Models for Drilling Process Automation: Equations and Applications [Text] / F. Florence, F. P. Iversen // Publisher Sociaty of petroleum Engineers. SPE Drilling Conferfence and Exhibition. – Nero Orleons, USA, Luisiana, 2010. – 16 p.
11. Gandzhumyan, R. A. Matematicheskaya statistika v razvedochnom burenii [Text] / R. A. Gandzhumyan. – Moscow: Nedra, 2013. – 210 p.