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ON THE FEASIBILITY OF USING TECHNOLOGIES FOR OPERATIONAL FORECASTING OF ABNORMAL RESERVOIR PRESSURES IN OIL AND GAS WELLS OF SOCAR

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A B S T R A C T

The article analyzes methods and technologies for predicting zones of abnormally high reservoir pressure (AHRP) when drilling oil and gas wells. Forecasting these zones is considered as one of the main methods for increasing the efficiency of drilling operations. Some methods of AHRP are reviewed, as well as the signs used for this purpose. The advantages of methods that use dependencies between technical drilling parameters are substantiated. Such methods enable us to predict high pressure zones in real time, and without stopping drilling. A brief chronology of the development and improvement of this class of methods is noted. A method included in this class is proposed. This method can also calculate the density of the weighted drilling mud to counteract the abnormal pressure. The method is based on the principle of mathematical calculation of the dependence of the mechanical drilling speed on a number of other mechanical drilling parameters. As a part of the SOCAR «Scientific Foundation» grant project, the use of AHRP forecasting methods in SOCAR practice was monitored and the results were provided. The feasibility of using a system created based on this method in SOCAR wells is substantiated. A brief summary of the principle of forecasting, the operation of functional blocks and the system is provided. An algorithm for the system's operation was developed. Based on this algorithm, a control program was written in the C++ programming language. The operability of the system was tested using laboratory experiments based on the method of computer simulation.

Keywords: oil and gas wells; AHRP; accidents and complications in wells; forecasting AHRP; forecasting AHRP in SOCAR; modernized forecasting method; forecasting system.

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Introduction

Macroeconomic indicators of many countries substantially depend on the oil and gas sector. Thus, oil, gas and oil products constituted 92.5% of total exports of our country in the past year. The effectiveness of operations in this sector is primarily related to the level of technological development employed in the drilling, construction and well exploitation processes. It is known that any type of well drilling and exploitation is accompanied with several accidents and complications (AC) due to abnormal reservoir pressure which leads to lower labor productivity. On the other hand, a number of serious accidents and complications can result in significant loss of oil and gas, environmental pollution and human casualties. Eliminating accidents and complications may lead to significant loss of time, human resources and financial means. In many cases, AC occurs as a result of abnormally high reservoir pressure (AHRP). Hence, timely detection and forecasting of AHRP zones is deemed as one of primary methods of increasing work efficiency. For this purpose, leading oil and gas companies utilize modern technologies and systems developed based on forecasting methods. Research shows that given their multiple advantages, systems developed by employing dependencies between mechanical drilling parameters (MDP) are more widely used with the purpose of forecasting AHRP zones.

Global experience shows that abnormally high-pressure zones are encountered during well drilling in all petroliferous provinces. This situation is especially characteristic for geological conditions of the Baku Archipelago and Southern Caspian Depression. On the other hand, it is essential to expand the projected depth of wells for the extraction of hydrocarbons. This situation increases the probability of encountering abnormally high pressure zones and makes the forecasting of such zones even more relevant. Collected data shows that one of the primary causes of the emergence of AC during well drilling is the existence of AHRP zones or abnormally high steam pressure zones in drilled rocks [1, 2].

Our research shows that countries that do not utilize modern achievements of geologo-geophysical sciences, modern engineering and technologies, as well as forecasting methods of abnormal pressure during drilling of oil and gas wells witness AC more often and these cases cause substantial damages.

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As an example, we can review the damage from a strong open gas fountain caused by AHRP during the drilling of gas well No. 90 in the Bulla-Deniz field (horizon VIII, projected depth 5800 m, Girmeki Sandy Bunch). The fountain existed for 68 days and caused daily losses: 8 million m^3 of gas condensate, 704 tons of oil, and substantially polluted the environment. Over the past 10 years, more than 88300 hours were spent to eliminate ACs that occurred in wells in the offshore fields of Azerbaijan alone; 54 wells were cancelled [3].

The paper presents a method facilitating the forecasting of AHRP zones based on MDP wells.

Methods and materials

The methods of evaluation and forecasting of abnormalities of reservoir pressure during the drilling process can be primarily divided into three groups:

- methods based on the utilization of data collected from geophysical exploration of wells.
  While this method has a higher accuracy in comparison with other methods, forecasting data is obtained with some time delay; as a rule, collection of this data requires a series of complex and expensive logging operations and halting of drilling.
- methods based on detecting MDP figures that exceed permissible limits. In most cases, detection is carried out via simple technical means or visual drilling brigade and has a low forecasting accuracy;
- methods based on the detection of patterns of change of dependencies between MDP. Methods included in two latter groups have a number of advantages: data is gathered in online mode (some methods have specific delays), and most importantly, they do not require stopping the drilling, etc. Although the accuracy of methods in the latter group is higher than the methods in former groups, their technical implementation as a forecasting tool is quite complex. The operational principle of these systems is based on formula-based computations developed on the basis of mathematical formalization of the patterns of changes in dependencies between the MDP and allows to fully automate the forecasting process. To increase the accuracy of the system, the proposed method can be utilized in combination with one or more simple forecasting methods of the second group mentioned below [4-5].
- torque of drilling tool (TDT)– (real-time method);
- hook load increase (real-time method);

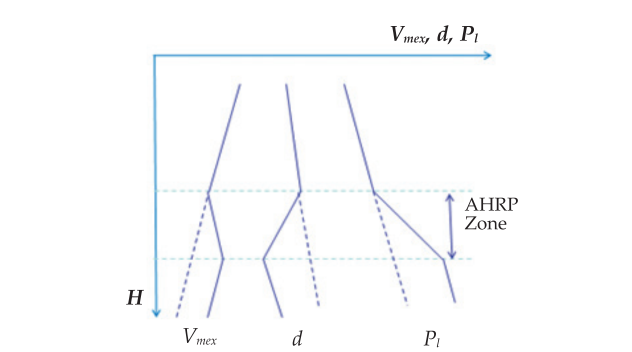

Fig. 1. Correlation between V_{mex}, d, and P_l

- pressure at the outlet line of the drilling mud (DM) pump - (delay mode method);
- Change of DM gas content, DM density, DM level in receiving reservoir (delay
- mode method);
- DM temperature in discharge line (delay mode method), etc.

Clearly, implementation of these methods/systems provides a higher level of forecast in deposits, where the lithological structure of rocks is sufficiently stable. Moreover, important factors include the accuracy of construction of wells indicated in the project documentation, lithological-stratigraphic characteristics of sections, expected complications, density of drilling mud (in a joint pressure schedule), as well as equivalent gradient pressure (in pressure schedule), accounting of practical results of drilling of closely located wells, etc.

The dependence of mechanical drilling speed (MDS – V_{mex}) on MDP and characteristics of rock drillability has been known to experts since the mid-20[th] century. In general, this dependency can be expressed as below:

$$V_{mex}=nf_1(P_y/D_{qa})\cdot f_2(V_{fs})\cdot f_3(T_{qa})\cdot f_4(\Delta_p) \quad (1)$$

where n – is a coefficient representing the characteristics of rock drillability; $f_1(P_y/D)$ – a function characterizing the impact of load on DT and DT diameter; $f_2(V_{fs})$ – a function characterizing impact of DT rotation speed; f_3 (T_{qa}) – a function considering the degree of dullness of DT; f_4 (Δ_p) – a function considering the differential pressure.

First mathematical expression of dependence between some MDP was presented in a paper by Bingam M.G published in «Oil and Gas» Journal in 1964 with the following formula [6]:

$$V_{mex}=a(V_{fs}/D_{qa})^d \quad (1)$$

where, V_{mex} – mechanical drilling speed, ft/min; V_{fs} – drilling tool rotation speed, cycle/min; D_{qa} – drilling instrument diameter, inches, a – lithological coefficient; d – rock density index.

Two years after, mathematicians Jordan and Shirley solved the above presented mathematical equation for d-exponent (hereafter, d). Moreover, they included coefficients that account for measurement units used at that time in the US oil industry. On the assumption that a=1 (in case of sufficient stability of lithological conditions), they obtained the following formula for d-exponential [7].

$$d \approx \frac{\lg\left(\frac{V_{mex}}{18V_{fs}}\right)}{\lg\left(\frac{0.067P_y}{D_{qa}}\right)} \quad (3)$$

where, V_{mex} – foot/min; V_{fs} – cycle/min; D_{qa} –inches; P_y – load on drilling tool – pounds.

Analysis of this formula shows that d function allows for tracking the degree of compaction/porosity and differential pressure. In other words, there is a strong correlation between reservoir pressure and V_{mex} and d parameters: when opening porous reservoirs suing DT, depending on the change in the value of d parameter, it is possible to evaluate abnormally high reservoir pressure and detect its zones.

Idealized graph of this correlation can be presented in the following manner (fig. 1).

As seen from diagram, in normal mode with depth increase, reservoir pressure increases along the «normal seal line» (curve), whereas MDS decreases linearly inversely. Correspondingly, the value of *d* function increases. From the moment of opening of porous layers (while entering AHRP zone), reservoir pressure P_l increases abruptly, and rocks are drilled faster, i.e., V_{mex} increases suddenly. In accordance with the change in these parameters, the value of *d* function increases monotonically over the whole AHRP zone. Hence, the pattern among MDP can be used for the evaluation of high reservoir pressure and AHRP zone forecasting.

The proposed function of *d*-exponent practically remained as the only method of detecting and forecasting AHRP zones for several decades. Thereafter, this method was improved by other authors and dozens of options were developed, as the dynamics of the increase or decrease of MDS can be changed and masked by the impact of other factors, for example, lithological structure of rocks, rotating speed of DT and its hydraulic characteristics (for example, level of dullness), etc. However, despite its shortcomings, this method is still widely used today.

Discussion of results and findings

As members of a working group, the authors developed several methods of forecasting abnormal pressure areas. Two of these methods are protected by certifications of authorship for inventions. These methods are based on the principle of detecting the change (decrease) of fluid density as a result of a gas leak to DM [9] and deviation of mechanical drilling speed from a probable limit [10] as a result of AHRP. Devices developed based on these methods have been applied in oil and gas production division named after Narimanov (Sangachal city) of «Azneft» PA and have demonstrated high effectiveness.

Two years ago, within the framework of a grant project (21 LR-HAHA) conducted with the financial support of the «Scientific fund» of SOCAR a monitoring was carried out with the purpose of determining technologies and methods used in the AHRP forecasting in the drilling practice of SOCAR in the «Integrated Drilling Works» trust of SOCAR, the «Drilling and Operation Engineering» department of the «Azneft» Production Association and the Closed Joint-Stock Company «Ekol Engineering Services». The outcomes of monitoring are presented below.

As seen from the table, the methods employed to forecast AHRP in the drilling practice of SOCAR are mainly those from above-mentioned first and second groups: methods based on the functional dependencies between mechanical drilling parameters are not employed. However, methods included in this group would allow for obtaining forecasting data in real-time mode and do not require stopping the drilling. We discussed this issue with designated staff members at SOCAR and they associate non-utilization of these systems with their low forecasting accuracy and high price. Indeed, these systems have a relatively low forecasting accuracy (≈70%). It is also known that, in practice, one or more simple forecasting factors included in the second group are used alongside with this method in order to increase the accura-

Table

Monitoring outcomes

	Forecasting method	Forecast recording time	Used in SOCAR
1	Based on mechanical drilling parameters.	During drilling (real-time mode)	
1.1	*d*-exponent		-
1.2	Modernized versions of *d*-exponent		-
1.3	Mechanical drilling speed		+
1.4	Rotor torque		+
1.5	Hook load etc.		+
2	Based on the parameters of circulation system and DM		
2.1	DM level in receiving reservoir		+
2.2	DM circulation speed		+
2.3	DM pump outlet pressure		+
2.4	Change in gas content of DM	During drilling (with delay)	+
2.5	Change in DM density		+
2.6	Change in DM temperature at wellhead etc.		+
3	According to sludge analysis		
3.1	Lithological structure		+
3.2	Clay factor and clay density		+
3.3	Volume, shape and size of parts		+
3.4	Gas quantity in sludge etc.		+
4	Wireline logging		
4.1	Electricity logging		+
4.2	Acoustics logging		+
4.3	Neuron/density logging		-
4.4	Gamma logging etc.		+

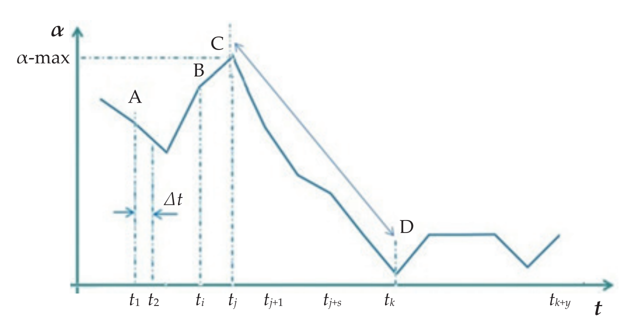

Fig. 2. Forecasting principle of AHRP zones

cy of these devices (in automated mode). For instance, BP company also applies forecasting systems of «Schlumberger» company (US, France) developed on the basis of an improved version of this method in ACG deposit in the deep seabed zone of Azerbaijani sector of the Caspian Sea. Although foreign companies use «managed pressure drilling» technology (MPD) including drilling at depression, the use of this class of equipment allows for greater savings of drilling mud. On the other hand, it is known that usually, in order to «insure» against the likelihood of oil and gas show, accidents and complications in practice, drillers work in a strong repression drilling mode (even if there is a possibility of hydraulic fracturing pressure and drilling mud loss). Until today, MPD technology, including drilling in depression, have only been tested in exploratory deposits in SOCAR's practice [11].

In regard to high costs of this class of forecasting system, it must be noted that, even modern forecasting systems based on the improved classic d-exponent method cost no more than several hundreds of thousands of euros. Considering the above mentioned, we think that it is purposeful to apply forecasting systems developed on the basis of functional dependencies between mechanical drilling parameters in SOCAR's practice.

Within the grant project, another improved version of the classic d-exponent method was developed, and a model system based on this method was tested by conducting laboratory experiments of computer modelling. The results of the study were presented in an international conference [12].

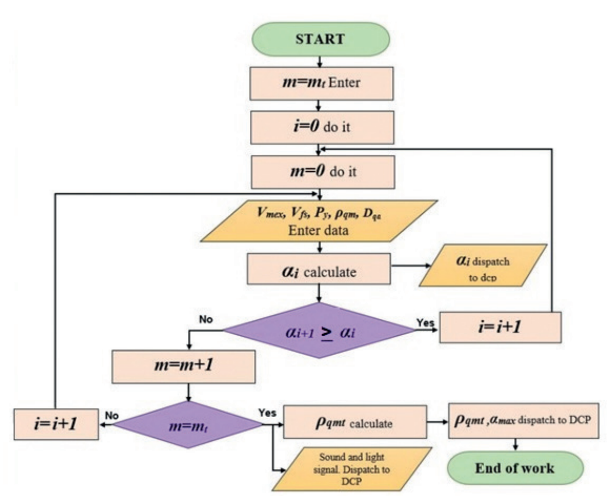

Fig. 3. Algorithm for the forecasting system

Dependencies among mechanical drilling speed and other MDP were used during the development of the method. Mathematical expression of the method is as follows:

$$\alpha = \frac{\lg \frac{V_{mex}}{60V_{fs}}}{\lg \frac{P_y}{\rho_{qm} D_{qa}^2}} \tag{4}$$

where, V_{mex} – mechanical drilling speed, meter/hr; V_{fs} – DT rotating speed, cycle/min; P_y – DT load, kg; ρ_{qm} – drilling mud density, kg/m^3; D_{qa} – DT diameter, meter.

As observed, this formula includes the parameter of DM density. This allows for considering the required density of DM according to equations (5) and (6) for restoring the disrupted pressure balance ($-\Delta P$) between hydrostatic and reservoir pressure after detecting the zone of high pressure based on the function.

$$\rho_{qm} = \frac{P_y}{10^n D_{qa}^2} \tag{5}$$

where,

$$n = \frac{\lg \frac{V_{mex}}{60V_{fs}}}{\alpha_{\max}} \tag{6}$$

The principle of detecting AHRP zones using the proposed method can be illustrated with the following graph (fig. 2).

As indicated above, if the drilling process continues under normal reservoir pressure, the average value of α increases monotonically with the increase in the depth (deviation of small amplitude is not considered). From the moment of opening of porous AHRP zone using a DT, MDS increases abruptly, and correspondingly, the value of α decreases monotonically m times during a certain $N\Delta t$ (Δt – inverse value of MDP sensor sampling rate) period. The value of m is selected experimentally depending on the reservoir thickness, drilling mode and other parameters indicated in the project documentation of the well. During t_1-t_j period, the value of α in the graph has decreased only by half (during $2\Delta t$, N=2), and is not considered an anomaly zone detection case, as it is lower than m. As the value of α in the CD section (in t_j-t_k interval) is constantly decreasing N=m times, the reservoir drilled during this period is identified as AHRP zone. Starting from this moment, the density of increased-weight DM is calculated for counteracting abnormal pressure according to derived equations (5) and (6).

Working algorithm (fig. 3) and management software were developed in C^{++} programming language based on the proposed method. The manipulation of system operation was tested through experiments conducted using a computer modelling method. An array consisting of real MDP values was used as input data. This data is entered into the system manually with two methods: sequentially for each calculation session or as a data block placed in the program code for automatic input.

MDP are transmitted from digital device sensors mounted on the well platform to the block which generates input signals of the system where they are subject to preliminary processing (clearing from interferences, formatting in accordance with the requirements of the input/output protocols of the computer, etc.). From here, signals enter the input of the computing device, and the system is launched:

the value of *a* function is computed based on current MDP values and displayed on driller's control panel (DCP). The computation cycle is repeated until the value of *a* function does not decrease consecutively and monotonically $m=m_t$ times. At the same time, sound and light warning signals are sent to the DCP. The value of *m* is selected experimentally depending on the strength of the formation, drilling mode and other parameters listed in the project documentation of the well. From this moment onward, the system computes the required density of DM based on current values of function arguments and a-max obtained from the sequences of values of *a*, according to formulas (5) and (6). The result output is sent to DCP.

Below is a part of the program developed based on the specified algorithm for calculating the value of function *a* for the periods of label1 and label2 command labels.

Note: The notation of parameters in formulas and algorithm is changed in the program code in accordance with the requirements of C^{++} programming language:
V_{mex}=Vmex; V_{fs}=Vfsc; P_y=Py; ρ_{qm}=Roqm (required value of DM density); D_{qa}=Dqa; α_{max}=alfamax; m_t=mteleb; α_i=alfai (α_i-current value of *a*-function).

```
#include <iostream>
#include <cmath>
#include <windows.h>
using namespace std;
float Vmex, Vfsc, Py, Dqa, Roqm;
float nn, Roqmt, alfai=0.0, alfaiyeni, alfamax=-100.0;
int i, m, mteleb;
int main() {
  label_start:
  cout << "\n label_start - Enter mtələb:  ";
  cin >> mteleb;
  i = 0;
  label1:
  std::cout<<"Label1" ;
  m = 0;
  std::cout <<"   m = "<<m;
  label2:
  std::cout<<"\nLabel2" ;
  std::cout << "\n Mechanical drilling speed-m/hr: ";
  std::cin >>Vmex;
  std::cout << "\n Rotating speed of drilling tool – cycle/min: ";
  std::cin >> Vfsc;
  std::cout << "\n Load on drilling tool - kg: ";
  std::cin >> Py;
  std::cout <<"\n Drilling mud density -g/sm 3: ";
  std::cin >> Roqm;
  std::cout << "\n  Diameter of drilling instrument -sm: ";
  std::cin >> Dqa;
  alfaiyeni = (log10(Vmex / (60 * Vfsc))) / log10((Py) / (Roqm * Dqa * Dqa));
  alfaiyeni = abs(alfaiyeni);
  if (alfai==0.0) {alfai = alfaiyeni;}
  std::cout << " i=" << i << "  alfaiyeni= " << alfaiyeni << "\n ";
```

Let's note that the accuracy of the forecasting of this group of systems is mostly dependent on the accuracy class of digital devices measuring DM density. Currently, such devices with various functions (and prices) are manufactured in several countries, including Russia. Some of these devices are outlined in [13]. The team under the supervision of authors proposes to test an experimental sample of the system developed based on the proposed method during the actual drilling process of SOCAR company.

Conclusion

This paper reviewed the forecasting issues of AHRP zones during the drilling of oil and gas wells in SOCAR practice and the following results were obtained:

1. The importance of forecasting of AHRP zones is substantiated for the purpose of avoiding accidents and complications caused by abnormal reservoir pressure and increasing the effectiveness of oil operations.
2. A monitoring was conducted to determine methods (systems) used for the forecasting of AHRP zones in SOCAR and findings were presented. It emerged that methods based on functional dependencies between mechanical drilling parameters are not used.
3. An improved version of the classic *d*-exponent method is proposed for the forecasting of AHRP zones in the operational mode.
4. This paper proposes a formula for computing the density of the drilling mud subject to weighting for the purpose of compensating abnormal pressure at the time of detection of AHRP zones.
5. A system working algorithm is developed on the basis of the proposed method and a control program is written in C^{++} programming language. System functioning is tested through laboratory experiments conducted using the computer modelling method.

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