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OPTIMIZATION OF TECHNOLOGICAL PARAMETERS OF AIRLIFT OPERATION WHEN DRILLING WATER WELLS

Purpose. Development of a methodology for optimizing the technological parameters of the airlift operation, based on the analysis of the pressure balance in the annulus and in the drill string that occurs during drilling.

Methodology. The tasks were solved by a complex research method, which includes a review and generalization of literary and patent sources, analytical studies on existing methods for optimizing the technological parameters of drilling with reverse circulation using an airlift.

Findings. It has been established that in the study on the airlift circulation method during rotary drilling with reverse circulation, an important role is played by the analysis of the pressure balance arising in the course of drilling in the annulus and in the drill string. It takes into account both hydrostatic pressures and pressure losses for pumping water and water-air mixture. A technique has been developed for assessing the effect of rate of penetration on circulation parameters.

Originality. For the first time, it has been shown that the analysis of the pressure balance makes it possible to establish, with a given accuracy, the average effective values of the output parameters: the density of the water-air mixture, its upward flow rate, and the air flow rate at a given velocity of the upward flow of water as it approaches the mixer.

Practical value. The proposed technique makes it possible to establish the dependence of the values of the output parameters on the depth of the well, as well as the required compressor performance to provide a given drilling fluid flow rate.

Keywords: *reverse circulation, airlift, Mangistau Peninsula, Samskoye field*

Introduction. The Republic of Kazakhstan is known in the world as a country with large reserves of natural resources. Largely due to their presence, the country manages to develop its economic, scientific and cultural potential. At the same time, Kazakhstan has limited volumes of one type of natural resources, namely water resources. In terms of per capita indicators, Kazakhstan cannot be classified as a country with an acute shortage of water resources. But the uneven distribution of water sources throughout the country, as well as their irrational use, greatly complicates the solution of the problems of supplying water to the population and the economic complex in the required volume and guaranteed quality.

According to the Concept of the State Program for Water Resources Management of Kazakhstan for 2020–2030, by 2040 water consumption will increase by 56 %, and water deficit will be about 12 billion m^3.

On the territory of the Mangistau Peninsula, where large deposits of hydrocarbons are concentrated, there is a critical situation with water supply. A typical groundwater deposit here is the Samskoye field, which can play an important role in the water supply of the city of Zhanaozen. A number of wells have been drilled here which are distinguished by a low flow rate; their depth does not exceed 50 m, and their diameter is 150 mm, while according to the Concept of water supply of the Mangistau region, the total water withdrawal from all wells does not exceed 18 % of the explored reserves. It is obvious that the methods of construction of water wells do not meet modern requirements.

Literature review. Well drilling efficiency largely depends on the right technological parameters. These include: weight on the bit (WOB), revolution per minute (RPM), drilling fluid flow rate and its parameters. Thus, research aimed at optimizing drilling technology can be conditionally divided into three large groups. The first group includes works that analyze the mechanical interaction in a bit-rock pair. As a rule, the search here is aimed at finding the best ratio of WOB and RPM [1]. The second group includes works analyzing the composition and properties of the drilling fluid. And to the third, works devoted to optimization of drilling fluid circulation, by improving the cooling of the bit and bottomhole and the removal of cuttings from under the bit along the wellbore to the daylight surface.

This work is devoted specifically to the issues of improving the quality of circulation during of water wells drilling.

There are many difficulties in well drilling with groundwater and large diameter wells with direct circulation of drilling fluid. The main reason for this is that due to the large drilling diameter, there are problems with cuttings to the surface, which can lead to well failure, long drilling period and high cost. The use of the reverse circulation process can effectively increase the rate of penetration (ROP), reduce the cost of the project, and reduce the labor intensity of the process. Due to the high rate of the upward flow of the drilling fluid (usually above 2 m/s), large diameter cuttings can be brought to the surface, and therefore, the ROP can be increased. The ROP increases as the immersion depth of the mixer increases. In the case of good wellbore stability, groundwater can be used directly as drilling fluid, which simplifies the drilling fluid circulation system. The reverse circulation drilling process is also a fluid circulation process, which can effectively protect the reservoir. Using this method, the ROP increases by about 30 % compared to direct circulation drilling [2].

Rotary drilling with reverse circulation allows getting wells up to 1500 mm in diameter [3]. The drilling fluid flows by gravity from the settling tanks to the casing string at the wellhead, descends through the annulus, clean the bottomhole and the drill bit, and then rises along the drill string and returns to the settling tank. It has been proven that in order to avoid collapses, it is necessary that the distance from the wellhead filled with water to its static level be at least 3 m [4].

After analyzing the characteristics and operating principles of traditional direct circulation drilling technology and reverse circulation airlift drilling technology in combination with the specific requirements of drilling wells for the development of groundwater reserves, the authors of [5] summarize that reverse drilling technology is necessary and much more effective, has the best technical support and will play an increasingly important role in water well drilling in the future.

Drilling wells under conditions of drilling fluid loss is an important problem in water drilling. The traditional way to solve it is to install casing strings. However, their installation is most expedient only after re-drilling the entire cover of unproductive rocks. At the same time, the losses zone can be significantly higher than the productive horizon.

In such cases, it is most expedient to use insulating plugging of the loss horizon in various ways [6]. This operation, although absolutely necessary in direct circulation, still leads to a significant increase in the time spent on well construction.

Reverse circulation drilling effectively solves the problems of silting of the aquifer and loss of drilling fluid in the well [7].

The efficiency of drilling with reverse circulation under drilling fluid lost conditions is highly dependent on the filtration effect. In [8], a simulation experiment was conducted, the filtration effect was quantified as the mass of water loss measured at a flow rate of 4.00 to 8.00 m^3/h for reverse and direct drilling fluid circulation. The results showed that: optimal flow rate is achieved with minimal filtration effect; there is a point where the positive and negative effects of increasing flow rate on filtration are the same, and filtration increases monotonically with flow.

While drilling a well for shale gas in Changning, Sichuan Province (China), field tests of gas injection into the annulus with gas lift reverse circulation were successfully carried out. Drilling fluid losses decreased by 83.6 %. The expediency of application of drilling technology with reverse circulation of gas-lift annular gas to solve the problem of lost circulation during drilling is confirmed. The key parameters of the drilling technology with reverse circulation and airlift gas injection are the volume of gas injection and displacement of the drilling fluid, the change of which regulates the bottomhole pressure [9].

Analyzing the cost of drilling wells, researchers identify three characteristic trends:

1. Well costs increase exponentially with depth due to more difficult drilling conditions.
2. Well cost uncertainty increases with depth due to increased likelihood of problems and less predictable drilling conditions.
3. Deep wells have a positive cost probability distribution [10].

Thus, it is very important to maximize the speed of well construction through efficient drilling technology.

The authors of [11] indicate that drilling with direct circulation of drilling fluid is usually used to construct large-diameter wells. It has the disadvantages of low drilling fluid flow rate, poor particle holding capacity, severe failure recurrence, low drilling efficiency, high drill bit wear, high energy consumption and high accident rate, which can be effectively improved by reverse circulation drilling technology, using airlift.

Reverse circulation drilling has proven to be highly effective in drilling wells for various purposes.

The scheme of drilling the ore zone using the airlift method for the extraction of uranium ore by underground borehole leaching was tested on operating technological wells of Volkovgeologiya, with an average total depth of 300–500 m [12]. Drilling with a reverse circulation of drilling fluid is a promising direction in the conditions of clogging of pores and formation fractures, resulting in a decrease in its permeability. Aquifers reverse circulation gives the greatest effect compared to other methods while maintaining the reservoir porosity and permeability natural conditions. A fluid column presence in the well provides necessary stability of the well walls. In the opening productive layers process due to the slurry suction from the bottomhole, their porosity and permeability natural conditions are preserved. Of all modern methods, this method allows opening productive formations with large diameter wells (up to 500 mm and more) [12].

In mine exploration, traditional core drilling has such problems as long well construction time and high cost, while reverse circulation drilling has high drilling efficiency and low cost [13].

According to [14], compared with traditional core drilling, drilling with reverse air circulation increased drilling efficiency by 70–90 % while reducing costs by 30–50 %, the number of accidents during drilling decreased by 60–70 %, and there was no drilling fluid pollution in the drilling process, and less dust, which meets the requirements of environmental protection.

Airlift reverse circulation drilling showed high efficiency when drilling geothermal wells in China [2, 15].

The use of airlift drilling technology with reverse circulation is possible even in the construction of ultra-deep wells. For example, using this technology, the construction of a well with a depth of 4200 m was successfully completed, which is the deepest geothermal well in China [7].

Note that another possible application of reverse circulation with the help of an airlift is not drilling a well, but expanding it with the help of jets [16].

Unsolved aspects of the problem. Currently, a number of reverse circulation mechanisms have been developed during well drilling: airlift pumps, submersible piston pumps, devices that convert the direct flow of drilling fluid in the bottomhole zone into counterflow, etc. However, reasonable recommendations lack the choice of parameters for reverse circulation mechanisms and a large number of design drawbacks hinder the wide practical application of this drilling method [8].

A significant factor that reduces the efficiency of well drilling with reverse circulation is the uncertainty of airlift operating conditions. This is due to the fact that the depth of the well is constantly changing, the pressure in the annular space and in the drill string, the depth of the mixer immersion are changing, which means that the optimal parameters of the airlift are changing. Currently, there is no method for determining the parameters of airlift operation in changing drilling conditions.

Thus, the **purpose of the article** is to develop a methodology for optimizing the technological parameters of the airlift operation, based on the analysis of the pressure balance that occurs during drilling in the annulus and in the drill string.

Methods. The tasks were solved by a complex research method, which includes a review and generalization of literary and patent sources, analytical studies on existing methods for optimizing the technological parameters of drilling with reverse circulation using an airlift.

Results. The Samskoye field is composed of Quaternary deposits and has an area of 1500 km^2. Groundwater horizons have the form of lenses of various shapes and sizes. According to the degree of mineralization of water, they are divided into two groups. The first includes fresh waters with salinity up to 1 g/l. The second features water with mineralization – up to 3 g/l. They are suitable for the needs of agriculture. Aquifers are represented by fine-grained sands with a filtration coefficient of 5.5–7.0 m/day. The host rocks are loams, sandy loams, and sandstones on lime cement. The fresh water depth ranges from 1.5 to 44 m, their thickness is up to 39 m with an average value of 14 m. Brackish waters are located below and are separated by layers of aquicludes.

In [17], based on a study of the geological and technical conditions of the Samskoye field, it was substantiated that the use of a rotary drilling method with reverse circulation allows a manifold increase in well flow rate; reduce their required number; improve the quality of produced water; drastically reduce the well completion time; significantly lengthen the time of operation of wells; provide high ROP; reduce the cost per cubic meter of produced water.

Figure shows how, in the process of drilling at a level close to the bottom of the well *1*, equilibrium is established between the pressures outside and inside the drill string *3*.

As a first approximation, the pressure outside the drill string can be taken as the hydrostatic pressure of the water column *13* of the corresponding height.

Inside the drill string there is a mixture *15* of water with air *14*, which is supplied there through the mixer *4* from the compressor *6* through the air channel *7*.

Due to the fact that the density of air is almost 1000 times lower than the density of water, the overall density of the mixture inside the drill string is lower than the density of water in which air is absent. For this reason, the hydrostatic pressure of the mixture column in the string is lower than the hydrostatic pressure of water in the annulus between the drill string and well *2*.

It should be noted that often the cause of complications and accidents during drilling is the discrepancy between the density of drilling fluids and the geological and technical conditions of drilling. One reason for this is that these parameters are measured manually and at long intervals. When drilling with reverse circulation of the drilling fluid, this problem is even more relevant, since when the compressor performance changes, the density of the drilling fluid also changes. In [18], a device was proposed for automatic measurement of drilling fluid density and cuttings content in it. Automatic density monitoring can significantly improve the efficiency of suction-assisted drilling and reduce the cost of dealing with complications and accidents.

Since the fluid always moves from a position where it is under some pressure to a position where the pressure is lower, the considered difference in hydrostatic pressures is the reason for the upward flow of drilling fluid inside the drill string.

The difference in hydrostatic pressure is used to overcome the fluid friction of the mixture against the inner walls of the drill string. The higher the flow rate is, the higher this friction

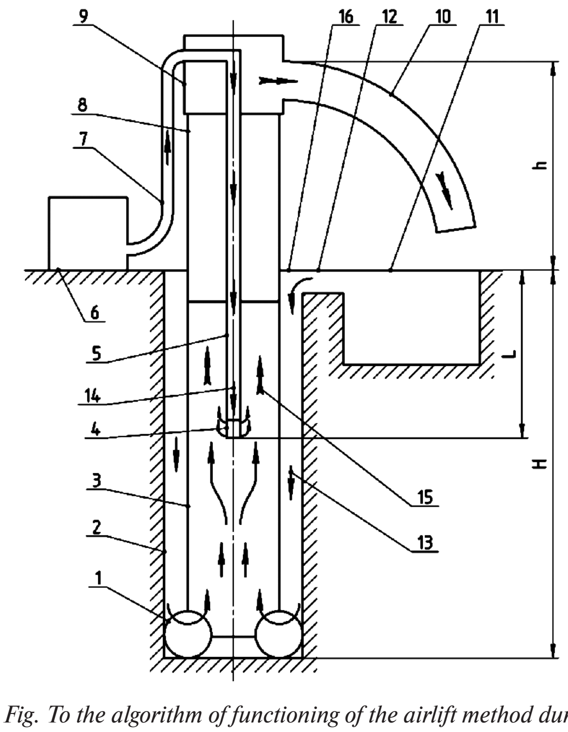

Fig. To the algorithm of functioning of the airlift method during rotary drilling with reverse circulation:

1 – drill bit; 2 – borehole wall; 3 – drill string; 4 – mixer; 5 – air duct; 6 – compressor; 7 – hose; 8 – kelly; 9 – swivel: 10 – throwaway sleeve; 11 – sump; 12 – gutter; 13 – water; 14 – compressed air; 15 – mixture; 16 – the surface of the earth; H is the depth of the well; L – mixer loading; h – the highest height of the mixture (the highest height of the swivel)

becomes. It follows that the greater the difference in hydrostatic pressures is (i.e., the higher the saturation of the mixture with air), the greater the pressure can be to overcome fluid friction and the higher the value of the upward flow rate can become.

From the foregoing, it follows that during drilling, an equilibrium is automatically established between the hydrostatic pressure of water in the space between the drill string and the walls of the well, on the one hand, and the sum of the hydrostatic pressure of the mixture and the pressure loss due to its movement inside the drill string, on the other.

The following studies are based on the constancy of the specified upstream rate U_W, since it is this rate that determines the efficiency of removal of destruction products from the bottom of the well and the ROP.

At a given rate U_W, the required flow rate of circulating water is

$$Q_W = U_W F_i, \quad (1)$$

where F_i is the bore area of drill pipes; U_W is the rate of the upward flow of water at the moment it reaches the level of the mixer and before it begins to mix with air.

The bore area of drill pipes is equal to

$$F_i = 0.785 d_i, \quad (2)$$

where d_i is the inner diameter of the drill pipe.

In contrast to the flow rate, which varies depending on the flow area of a particular section of the well, the Q_W value remains constant in any section of the circulation, including the annulus. This value remains constant even when (above the mixer) the water is only part of the resulting mixture.

With a constant volume of water circulating per unit time, the second component of the mixture, the volume of air, continuously increases as the mixture moves up the drill string due to a decrease in hydrostatic pressure (the physical law of Boyle-Mariot). An increase in the volume of the air in the mixture results in a corresponding continuous increase in the upflow rate of the mixture. However, the mass flow rate of the air supplied by the compressor remains constant, and therefore, an increase in volume leads to a decrease in the density of compressed air.

It was found in [19] that the initial pressure of the compressor depends on the depth of the well, the depth of the gas-liquid mixer run, the cuttings settling coefficient and the density of the drilling fluid.

When the mixture comes out to the surface, the air escapes from the hose *10* (Fig. 1) and the same constant volume of water Q_W is drained into the sump *11*. In the sump, this water is released from the sludge carried out and then returns through the chute *12* to the annular space of the well, forming a downward flow.

Let us consider the balance of external (with respect to the drill string) and internal pressures in more detail. This balance is expressed by the equation

$$P_O = P_I,$$

where P_O is the pressure outside the drill string; P_I is the pressure inside it.

The pressure outside the drill pipes consists of two components

$$P_O = P_S + P_D,$$

where P_S is the hydrostatic pressure; P_D is the hydrodynamic pressure (pressure loss) of the downstream.

Hydrostatic component of external pressure

$$P_S = \rho_W g L, \quad (3)$$

where ρ_W is the density of water (1000 kg/m^3); g – free fall acceleration (9.81 m/s^2), L – mixer load (distance from mixer 4 to the ground surface).

It should be borne in mind here that in (3), a part of the external hydrostatic water pressure in the area corresponding to the distance from the mixer to the bit is not taken into account, since this pressure is compensated by the same hydrostatic water pressure inside the drill string.

The hydrodynamic component of the external pressure (caused by fluid friction when water flows down the annulus) is determined by the Darcy-Weisbach formula

$$P_D = \rho_W \lambda_{WO} H \frac{U_{WO}^2}{2(D-d_o)}, \quad (4)$$

where λ_{WO} is the coefficient of hydraulic resistance to the downward flow; H is the depth of the well; D is well diameter; d_O is outer diameter of drill pipes; U_{WO} is the downstream rate.

The downstream rate is

$$U_{WO} = \frac{Q_W}{F_O},$$

where Q_W is the flow rate (volume of fluid flowing per unit time) of the circulating water and F_O is the area of the annulus.

$$F_O = 0.785(D^2 - d_O^2). \quad (5)$$

In (4), the coefficient of hydraulic resistance λ_{WO} to the movement of water flow in the annular space is determined using the Reynolds criterion. This criterion is

$$R_{EO} = \frac{\rho_W U_{WO}(D-d_O)}{\nu}, \quad (6)$$

where γ is the coefficient of dynamic viscosity. The coefficient of dynamic viscosity of water is $\gamma_W = 0.001$ Pa · s.

Let us determine the value of the Reynolds criterion for the downward flow of water in the annulus when drilling a typical well. Well diameter $D = 0.8$ m; drill pipes have an outer diameter $d_O = 0.146$ m and an inner diameter $d_I = 0.136$ m; the upward water flow rate $U_W = 2.5$ m/s is maintained.

According to (2), we obtain the area of the bore section of the drill string $F_i = 0.0145$ m^2; according to (1), the consumption of drilling fluid (water) $Q_W = 0.0362$ m^3/s; according to (5), the annulus area $F_O = 0.486$ m^2; and according to (3), the downward flow rate $U_{WO} = 0.0745$ m/s.

Substituting the necessary values into (6), we determine the value of the Reynolds criterion for the water flow in the annulus R_{EO} = 487,000 or $4.87 \cdot 10^5$. When the water flow moves in the annular space, if the value of the Reynolds criterion exceeds 10^5, then the flow moves in a turbulent mode, and the coefficient of hydraulic resistance $\lambda_{WO} = 0.024$ [20].

With such a coefficient of hydraulic resistance and known values of all other components included in (4), we set the value of the hydrodynamic component of the external pressure $P_D =$ = 20.4 Pa. For the conditions under consideration, this value is negligible.

Pressure losses inside the drill string also have static and dynamic components

$$P_I = P_{SI} + P_{DI}. \quad (7)$$

The hydrostatic component splits into two parts

$$P_{SI} = P_{S1} + P_{S2},$$

where P_{S1} is the hydrostatic pressure of the mixture

$$P_{S1} = \rho_M g(L+h), \quad (8)$$

where ρ_M is the average density of the mixture along the length $L + h$ (Figure).

The flow moving along the internal channel of the drill string carries with it particles of destroyed rock, which increase the overall density of the upward flow, and hence the hydrostatic pressure. The second term in (7) takes into account the growth of hydrostatic pressure depending on the sludge content

$$P_{S2} = \Delta_F g(H+h), \quad (9)$$

where Δ_F is the increase in the density of the upward flow due to the sludge contained in it.

With regard to drilling with direct circulation, the required cuttings removal rate is determined based on the maximum allowable increase due to its content in the density of the upward flow. The required cuttings removal rate is

$$U_F = \frac{D^2(\rho_F - \rho_W)U_D}{(D^2 - d_O^2)\Delta_F}, \quad (10)$$

where ρ_F is rock density, U_D is ROP.

The numerator of this formula contains:

- well diameter D, which characterizes the area of the bottomhole (the area over which its destruction occurs);

- the difference in parentheses corresponds to an increase in density due to the fact that the density of the rock exceeds the density of the drilling fluid (in this case, water);

- U_D – ROP characterizes the rock destruction rate.

The denominator of the formula contains:

- the value in parentheses, which characterizes the cross-sectional area of the annular space (through which the sludge rises during direct circulation);

- the maximum allowable increase in the upstream density. Under direct circulation Δ_F should not exceed 10 kg/m^3.

Transforming (10), we obtain the actual excess of the density of the upward flow due to the content of sludge in it at a known removal rate

$$\Delta_F = \frac{D^2(\rho_F - \rho_W)U_D}{(D^2 - d_O^2)U_W}.$$

Since, during reverse circulation, the cuttings do not rise along the annular space, but along the internal channel of the drill pipes, the diameter of this channel should be in the denominator of the formula.

Thus, we finally accept that for the sludge removal rate equal to the upward water flow rate U_W, the increase in the density of the upward flow is determined as

$$\Delta_F = \frac{D^2(\rho_F - \rho_W)U_D}{d_i^2 U_W}. \quad (11)$$

The hydrodynamic component of pressure inside the drill string includes three components

$$P_{DI} = P_{D1} + P_{D2} + P_{D3}. \quad (12)$$

The first component characterizes the pressure loss on the path of the upward flow of water from the bit to the mixer

$$P_{D1} = \rho_W \lambda_W (H-L)\frac{U_W^2}{2d_i}. \quad (13)$$

The coefficient of hydraulic resistance λ_W, as in the above case (10), is determined using the Reynolds criterion.

When water moves inside drill pipes, the Reynolds criterion is determined by the formula

$$R_{Ei} = \frac{\rho_W U_W d_i}{\nu}. \quad (14)$$

For the drilling conditions of a typical well, the rate U_W of water rise along the drill string from the bottom to the mixer is assumed to be 2.5 m/s. Given that the water density ρ_W is 1000 kg/m^3, its dynamic viscosity $\gamma = 0.0001$ Pa · s, and the inner diameter of the selected drill pipes is $d = 136$ mm, the Reynolds criterion determined by (14) is $3.4 \cdot 10^6$. This is higher than 10^5 and is therefore indicative of a turbulent regime. In this case, in f (13), the coefficient of hydraulic resistance to the movement of water along a circular channel is defined as

$$\lambda_W = \frac{0.0121}{d^{0.226}}.$$

The second component in the (12) P_{D2} is the pressure loss due to the increase in density due to the content of sludge in the upstream

$$P_{D2} = \Delta_F \lambda_W (H+h) \frac{U_W^2}{2d_i}. \quad (15)$$

Since the sludge particles are located in the water flow, (15) uses the same values of the hydraulic resistance coefficient λ_W and flow rate U_W as in (13) directly related to this flow.

The third component in the (12) P_{D3} is the pressure loss during the movement of the mixture

$$P_{D3} = \rho_M \lambda_M (L+h) \frac{U_M^2}{2d_i}, \quad (16)$$

where L is the distance from the surface to the mixer (the depth of its loading); h is the maximum lifting height of the swivel above the earth's surface; U_M is the average rate of the mixture lifting at the specified interval $L + h$, λ_M is the average value of the coefficient of hydraulic resistance during the movement of the mixture.

With the height of the lift and the decrease in hydrostatic pressure, the air bubbles coming from the mixer into the water flow become larger and larger. For this reason, the volume of the mixture of water and air increases, which means (with a constant bore section of the drill string) its rate, also increases. From the fact that, as shown above, water that does not yet contain air moves in a turbulent regime, it follows that this regime can be adopted even more for the movement of a mixture whose rate is higher. Therefore, we take $\lambda_M = \lambda_W$.

The pressure balance (9) for the drilling fluid circulation created by the airlift method, taking into account all the above components, takes the form

$$P_S + P_D = P_{S1} + P_{S2} + P_{D1} + P_{D2} + P_{D3}. \quad (17)$$

The terms of this equation are determined by formulas (3, 4, 8, 9, 13, 15, 16), respectively. Formulas (P_S, P_D, P_{D1}) contain the density values of water, formulas (P_{S2}, P_{D2}) contain the density of the sludge, formulas (P_{S1}, P_{D3}) contain the density of the mixture. The value of the density of water is known; the algorithm for determining the amount of density increase due to sludge is shown above (11).

The density of the mixture constantly decreases with its ascent from the mixer to the mouth. However, from (17) it is possible to determine its average, effective density. We write this equation as follows

$$P_{S1} + P_{D3} = P_S + P_D - P_{S2} - P_{D1} - P_{D2}. \quad (18)$$

Let us write out the content of the two terms on the left side of (18)

$$\rho_M g(L+h) + \rho_M \lambda_M (L+h) \frac{U_M^2}{2d_i} = P_S + P_D - P_{S2} - P_{D1} - P_{D2}.$$

Or, bracketing the common terms

$$\rho_M (L+h)\left(g + \lambda_M \frac{U_M^2}{2d_i}\right) = P_S + P_D - P_{S2} - P_{D1} - P_{D2}.$$

Where do we get the average density of the mixture

$$\rho_M = (P_S + P_D - P_{S2} - P_{D1} - P_{D2}) \Bigg/ \left((L+h)\left(g + \lambda_M \frac{U_M^2}{2d_i}\right)\right). \quad (19)$$

Having determined ρM, we find the average rate of rise of the mixture from it. To do this, we use the mass flow equation

$$Q_W \rho_W + Q_A \rho_A = (Q_W + Q_A)\rho_M, \quad (20)$$

where Q_W and Q_A are the volume flow of water and the average volume flow of air, ρ_W and ρ_A are the corresponding densities; ρ_M is the density of the mixture of water and air.

On the left side of the equation, we have the sum of the mass flow rates of water and air. Both of these terms are constants. However, both factors are constant in the first term, since water is incompressible. In the second term, only this product itself is constant (mass air flow supplied by the compressor), and the larger the first factor (volume flow), the smaller the second factor (density). Thus, Q_A represents the average effective air flow during steady drilling.

On the right side, the sum of the constant water flow and the average air flow is multiplied by the average density of the mixture.

Transforming (20), we obtain the average volumetric air flow

$$Q_A = \frac{Q_W(\rho_W - \rho_M)}{\rho_M - \rho_A}.$$

Since the density of the air (even compressed air) is negligible compared to the density of water, the air density can be neglected and then the average volumetric air flow will be

$$Q_A = \frac{Q_W(\rho_W - \rho_M)}{\rho_M}. \quad (21)$$

Average mixture consumption is

$$Q_M = Q_W + Q_A.$$

Substituting its value obtained from (21) instead of Q_A in this formula, we obtain

$$Q_M = Q_W \frac{\rho_W}{\rho_M}. \quad (22)$$

Where the average rate of the mixture is

$$U_M = \frac{Q_M}{F_i}, \quad (23)$$

where F_i is the bore area of the drill string.

Formula (19) already involves the average flow rate of the mixture U_M, which has not yet been determined. This problem is solved by the method of successive approximations used in computational mathematics. Specifically, in relation to this case, this method is implemented as follows.

In (19), as an unknown value of U_M, the closest possible value (based on general considerations) is substituted. For example, it is advisable to use the value of the water flow rate

$$U_M = U_W. \quad (24)$$

The value of ρ_M thus obtained by (19) is then substituted into (21, 22), and then a new value of U_M is obtained by (23). This new value, as well as the value originally adopted by formula (24), will also contain an error, but this error will be smaller. This new value is again substituted into (19) and the calculation procedure according to (21–23) will be repeated, and the error in finding the value of U_M will decrease again. With each repetition of the described procedure, the error will decrease more and more.

The described procedure is repeated until the value U_M found by (23) differs in absolute value from the previous value found by the same formula, less than by a predetermined negligible value δ. The condition is set

$$U_M(j) - U_M(j-1) < \delta, \quad (25)$$

where j is the serial number of the above repeated procedures.

The condition in (25) is interpreted as follows: if the difference in the value of the flow rate of the mixture $U_M(j)$ obtained during repetition number j compared with the value $U_M(j-1)$ obtained during the previous repetition number $j-1$ is less than the given value is negligible small error δ, then it is considered that the true value of the rate of rise of the mixture is found. At the same time, the true values of the flow rate-dependent values of mixture density ρ_M, air flow rate Q_A, and mixture flow rate Q_M were also found. If the condition in (25) is not met (the difference between the two subsequent values exceeds the allowable error), then the described procedure is repeated until the set condition is satisfied.

Formula (19) and related formulas (21–23) determine the output parameters of the computer model. It has been repeatedly emphasized above that these are average effective values and that they refer to the entire interval from the wellhead to the current drilling depth.

At the same time, it is obvious that the actual current values of these parameters are not constant, but change continuously and smoothly. In the direction of movement of the drilling fluid in the direction from the bottom up with a decrease in height, the hydrostatic pressure decreases all the time. For this reason, the size of the air bubbles released from the mixer increases accordingly, which, in turn, causes an increase in the volume of the water-air mixture and a decrease in its density. With an increase in the volume of the mixture and simultaneously with a decrease in its density, its flow rate increases

By dividing the well according to its depth into conditional intervals of the same length, we can calculate the change in density

$$\rho_{M\Delta}(i) = \rho_M(i) \cdot i - \rho_M(i-1) \cdot (i-1). \quad (26)$$

In this formula, $\rho_{M\Delta}(i)$ is the average density on some interval number i; $\rho_M(i)$ is effective density from the mouth to the lower boundary of i – that interval; $\rho_M(i-1)$ is the effective density from the mouth to the lower boundary of the previous interval. Index i is not only the number of the interval, but also the number of conditional intervals included in the distance from the wellhead to the depth of the well, i. e. to the lower limit of the considered conditional interval.

The example considers a 90 m deep well drilled with an airlift reverse circulation.

The well is conditionally divided into 3 equal intervals: 0–30 (interval number i = 1), 30–60 (i = 2) and 60–90 m (i = 3).

Upon reaching a depth of 30 m, the average effective value of the density of the water-air mixture ρ_M calculated by (19) turned out to be 576 kg/m the average density over this interval was 744 kg/m^3.

The fourth column of Table shows the products of the average effective density values by i, i. e. by the number of conditional intervals to which this density refers.

Finally, in the fifth column, according to (26), the values of the average interval densities are given as the differences between the products related to the considered depth and the depth of the previous arbitrary interval.

So, for a depth of 90 m, the product $\rho_M \cdot i$ = 2232 kg/m^3, the same product for a depth of 60 m is 1394 kg/m^3. The average density over the interval 60–90 m is equal to the difference between these two numbers, namely 838 kg/m^3.

Having determined the density $\rho_{M\Delta}$ in all the established intervals and substituting its values instead of the values ρ_M into formulas (21–23), we find the average interval values of the air flow rate $Q_{A\Delta}$, the mixture flow rate $Q_{M\Delta}$ and its upward flow rate $U_{M\Delta}$.

In the considered example, for simplicity, the depth of 90 m is arbitrarily divided into only three intervals of 30 m each. However, modern computer technology can easily cope even in the case when the size of the interval is many times smaller and, accordingly, the number of intervals (at the same considered depth) is the same number of times more. As a result, the plots of the dependence of the output parameters on the depth will look like a smooth curve.

Table

An example of determining the interval values for the density of the mixture in kg/m^3

H	i	ρ_M	$\rho_M \cdot i$	$\rho_{M\Delta}$
0	0	0	0	0
30	1	576	576	576
60	2	697	1394	818
90	3	744	2232	838

An important result of the above algorithms is the ability to set the required air supply by the compressor. Since the volume of air (like any gas) is inversely proportional to the pressure that acts on it, the compressor flow is usually referred to as atmospheric pressure. The compressor flow in relation to the airlift reverse circulation method can be found by the average air flow for the first (counting from above) conditional interval.

$$Q_{ABAR} = \frac{Q_{A\Delta 1}(\rho_{M\Delta 1} g(0.5h_1) + 10^5)}{10^5}. \quad (27)$$

In this formula, on the left there is the air flow rate, providing a given rate of rise of the drilling fluid, at atmospheric pressure (i.e. the required compressor flow). On the right in the numerator before the brackets there is the air flow in the first interval, and further in brackets there is the hydrostatic pressure in this interval (related to its middle) including the density of the mixture, the acceleration of gravity and the height of the interval. The factor 10^5 converts Pascals to atmospheres.

Let us continue the example given in table in relation to the search for the required compressor capacity.

The initial data are: depth of the first interval from above h_1 = 30 m (all subsequent initial data refer to the middle of this interval 15 m), density of the mixture (Table) $\rho_{M\Delta 1}$ = 576 kg/m^3, free fall acceleration g = 9.81 m/s^2; air flow, determined by (21). This formula involves water flow, which for 136 mm ID drill pipes and 2.5 m/s updraft (average for reverse circulation) is Q_W = 2.18 m^3/min. Formula (21) gives the average interval value of air flow $Q_{A\Delta 1}$ = 1.61 m^3/min.

Substituting the known values of all input quantities according to (27), we obtain the required compressor flow at atmospheric pressure Q_{ABAR} = 2.96 m^3/min.

Conclusions.

1. An algorithm for studying the airlift circulation method in rotary drilling with reverse circulation is developed, based on the analysis of the pressure balance in the annulus and in the drill string that occurs during drilling. The pressure balance takes into account both hydrostatic pressures and pressure losses for pumping water and water-air mixture.

2. A technique has been developed for assessing the impact of the ROP on circulation indicators.

3. Analysis of the pressure balance makes it possible to establish, with a given accuracy, the average effective values of the output parameters: the density of the water-air mixture, its upward flow rate and the air flow rate at a given upward flow rate of water as it approaches the mixer.

4. A technique has been developed for the transition from average-effective for a given depth values of the output parameters of airlift reverse circulation to their average interval values, when dividing the current depth into any arbitrarily given number of intervals.

5. The proposed technique makes it possible to establish the dependence of the values of output parameters on the depth of the well, as well as the required compressor performance to provide a given rate of drilling fluid.

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Оптимізація технологічних параметрів роботи ерліфта при бурінні свердловин на воду

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Мета. Розробка методики оптимізації технологічних параметрів роботи ерліфта, що базується на аналізі балансу тисків, які виникає в ході буріння, у кільцевому просторі та у бурильній колоні.

Методика. Поставлені завдання вирішувалися комплексним методом дослідження, що включає огляд та узагальнення літературних і патентних джерел, проведення аналітичних досліджень існуючих методик оптимізації технологічних параметрів буріння зі зворотно-всмоктуючим промиванням за допомогою ерліфту.

Результати. Встановлено, що при дослідженні ерліфтного способу циркуляції при обертальному бурінні зі зворотним промиванням важливу роль відіграє аналіз балансу тисків, який виникає в ході буріння, у кільцевому просторі і в бурильній колоні. У ньому враховуються як гідростатичні тиски, так і втрати тиску на прокачування води й водо-повітряної суміші. Розроблена методика оцінки впливу механічної швидкості буріння на показники циркуляції.

Наукова новизна. Уперше показано, що аналіз балансу тисків дозволяє із заданою точністю встановлювати середньо-ефективні значення вихідних параметрів: щільності водо-повітряної суміші, швидкості її висхідного потоку й витрати повітря за заданої швидкості висхідного потоку води при її підході до змішувача.

Практична значимість. Запропонована методика дозволяє встановлювати залежність значень вихідних параметрів від глибини свердловини, а також продуктивність компресора для забезпечення заданої швидкості промивної води.

Ключові слова: *буріння зі зворотним промиванням, ерліфт, півострів Мангістау, Самське родовище*

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