**Investigation of drilling fluid criteria and parameters determining the effectiveness of cuttings removal during the transition from laminar to turbulent flow regimes in the geological conditions**

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**Abstract**. This article focuses on the research and mathematical substantiation of drilling fluid criteria and parameters that ensure effective cuttings removal during well drilling in the geological conditions of Uzbekistan. The main attention is given to the conditions for the transition of drilling fluid flow from laminar to turbulent regime. The work involves constructing a mathematical model to optimize drilling fluid parameters. The first condition concerns selecting the density of the drilling fluid, which should prevent the inflow of formation fluids while simultaneously preventing formation fracturing. For this purpose, calculation inequalities (2) and (3) are formulated. The second condition defines the rheological parameters necessary to ensure a turbulent flow regime. Based on the analysis of the Reynolds number, which depends on the Hedstrom number, criterion constraints for kinematic viscosity were obtained. As a result of combining the density and viscosity criteria, along with the hydrodynamic conditions of drilling tool movement in (12), a complete mathematical model for the geological conditions of Uzbekistan is obtained in (13). This model serves as the basis for selecting drilling fluid parameters to increase the mechanical drilling rate while maintaining wellbore stability conditions.

**INTRODUCTION**

The efficiency of the drilling process directly depends on the hydrodynamic parameters and rheological properties of the drilling fluid, with the key aspect being the provision of optimal flow regime for cuttings removal [1]. This research is based on principles developed by leading specialists in the field of drilling and hydrodynamics [2-3].

Classical works in the field of drilling, presented in the studies of A. I. Bulatov, Yu. M. Proselkov, and S. A. Shamanov, laid the foundation for determining the main technological parameters. In particular, these works formulated the basic conditions for ensuring borehole cleaning, defining the minimum required value of the volumetric flow rate Q (formula (1)), as well as methods for calculating the total delivery of drilling pumps.

A key aspect in assessing pressure losses and cuttings removal efficiency is determining the flow regime (laminar or turbulent). According to generally accepted approaches, the transition from structural (laminar) to turbulent flow for viscoplastic fluids is determined by the critical Reynolds number. The formula, which takes into account the Hedstrom number, is also provided in classical sources.

The issues of selecting the drilling fluid density to ensure wellbore stability and prevent emergency situations are fundamental. The literature defines two antagonistic conditions:

- creating a back pressure that prevents the inflow of formation fluids (formula (2)).

- preventing formation fracturing (formula (3)).

While classical approaches provide recommendations for selecting safety factors and differential pressure, this work details and evaluates the minimum density value depending on the formation pressure and depth, which allows for more accurate application of formula (2) in practice.

It is worth noting the contributions of Zh. A. Akilov and M. S. Dzhabbarov, whose works on mathematical modeling of hydrodynamic processes include the pressure balance equation during the movement of drilling tools. This equation (12) is used in the current work to derive inequality (12), which limits the speed of the tool's movement and, consequently, prevents hydraulic fracturing.

The literature acknowledges that numerous rheological conditions for drilling fluids have been developed for various situations. In particular, standardized methods are used to determine rheological parameters:

Kinematic viscosity determination is performed in accordance with GOST 33768-2015, which ensures the accuracy and standardization of the initial data.

The calculation of dynamic yield stress and plastic viscosity is based on the methods described in the works of V. P. Ovchinnikov and N. A. Aksenova, using viscometer readings (FANN and VSN-3).

A criterion inequality (11) has been derived, which relates kinematic viscosity to the wellbore geometric parameters, density, and dynamic yield stress. This inequality guarantees a turbulent flow regime in the annular space, provided that the minimum flow rate required to clean the borehole is met.

A complete mathematical model (13) has been created, which combines rheological requirements for turbulence (inequality (11)), density criteria for preventing hydraulic fracturing and inflow (conditions (2) and (3)), and dynamic constraints on tool movement speed (inequality (12)).

Thus, the work not only relies on fundamental knowledge but also develops it by creating a comprehensive apparatus for the rapid selection of drilling fluid parameters, specifically adapted to improve drilling efficiency in the geological conditions of Uzbekistan.

**EXPERIMENTAL RESEARCH**

To ensure the cleaning of the borehole bottom from cuttings, the value of the volumetric flow rate Q is determined, which is then verified by checking the following condition [4]:

where a ∈ [0.35; 0.5] m/s for rotary drilling and electric drilling; a ∈ [0.5; 0.7] m/s for drilling with hydraulic downhole motors.

For the flow rate value Q, the diameters of the cylinder liners of the drilling pump are selected from reference tables, focusing on cuttings removal. The total pump output is determined [4] by the formula:

where m is the filling coefficient; n is the number of pumps; Qn is the pump flow rate at a given bushing diameter, /s.

The coefficient m is selected depending on the suction conditions of the liquids. When there is positive suction head, m=1. If suction is carried out from containers in the soil during water flushing, m=0.9, and with a clay solution, m=0.8 [4].

When selecting the density of the drilling fluid used during the drilling of a given interval, it is necessary to consider the following two conditions: creating a back pressure that prevents the inflow of formation fluids into the well and preventing hydraulic fracturing [4].

The first condition has the form

where ρ is the density of the drilling fluid, kg/; is the safety factor; is the formation pressure, Pa; g is the acceleration due to gravity, m/; is the depth to the top of the formation with the maximum formation pressure gradient, m; is the pressure loss.

According to existing guidelines, the following values are recommended for the formation counterpressure, expressed through the safety factor and the differential pressure

; at ;

; at ;

; at .

Thanks to the authors [3-5], a variety of conditions for the rheology of drilling fluid under different circumstances have been developed.

The density calculated using formula (2) must be checked for compliance with the second condition, which stipulates that the pressure of the drilling fluid in the annular space opposite each formation must be less than the fracturing pressure of that formation. The second condition is expressed as follows [1]:

where is the formation fracturing (loss) pressure, Pa; is the pressure loss during the circulation of drilling fluid in the annular space along the path from the bottom of the considered formation to the wellhead, Pa; luid content in the slurry flow without considering relative velocities; - slurry density, kg/; - depth of occurrence of the bottom of the considered layer, m; - mechanical drilling speed, m/s.

From condition (2), we compare and evaluate the minimum value of ρ:

from here

**RESEARCH RESULTS**

When > 2500 m, if the reservoir pressure is less than 50 MPa, then

If the reservoir pressure exceeds 87.5 MPa, then

At 1200 m < ≤ 2500 m, if the reservoir pressure is less than 25 MPa, then

If the formation pressure exceeds 50 MPa, then

When < 1200 m, if the reservoir pressure is less than 10 MPa, then

If the reservoir pressure exceeds 15 MPa, then

Otherwise, the required density of the drilling fluid is determined by calculations based on conditions (2) and (3).

Since the values of and varphi depend on the flow rate of the washing fluid, the second condition can only be verified after establishing the pump output. To calculate pressure losses due to friction during the movement of washing fluid without cuttings in pipes and the annular space, it is necessary to determine the flow regime, which dictates the selection of appropriate calculation formulas. For this purpose, the critical Reynolds number for the washing fluid flow is calculated, at which the transition from laminar to turbulent flow occurs.

This number for viscoplastic fluids is determined from the relationship [4].

Where Hedstrom number; μ - plastic (dynamic) viscosity of the drilling fluid, Pa·s; - dynamic yield stress, Pa. When fluid flows inside the drill string, the value of is taken as equal to the inner diameter of the drill pipes . In the annular space, is defined as the difference between the wellbore diameter and the outer diameter of the drill pipes [4].

If the Reynolds number of fluid flow in pipes R or in an annular space Rexceeds the calculated critical value R, then the flow regime is turbulent. Otherwise, the flow occurs in the structural regime. [4]

The values of R are calculated using the following formulas:

The values of R are calculated using the following formulas:

Comparing Rand R:

by substituting the corresponding values, we get

Setting , we obtain

simplified form

The difference between is much smaller than ; therefore,

From this it follows that the following relationship is always valid:

Means that the Reynolds number for fluid flow in pipes is always greater than the Reynolds number for fluid flow in the annular space.

If the Reynolds number of fluid flow in the annular space is greater than the calculated critical value , then the fluid flow regime in the annular space is turbulent.

From the above, it follows that to ensure a turbulent flow regime of the fluid in the annular space, it is necessary to select a drilling fluid that satisfies the following condition:

From formula (1) and the values of a, we always obtain:

by combining the formulas (4) and (5), we obtain

hence, it follows that according to the conditions for cleaning the bottomhole from cuttings (sm the above-mentioned relationship)

represents the transition period to turbulent flow regime. Therefore

and

must correspond to each other. From the properties of the inequality it is known that

from where

By combining formulas (6) and (7), we obtain the conditions for turbulent flow of washing fluids in the annulus space for cleaning the bottomhole from sludge:

It is known that

from which we have that the kinematic viscosity must always be less than the values determined by formula (8):

According to GOST 33768-2015, the kinematic viscosity , is calculated using the formula [2]:

where C- viscometer constant,; t- flow time, s; ;

- the geographical latitude of the place; h- the height above sea level, m;

V - capacity of the measuring tank, ; L - length of the capillary, m; D - diameter of the capillary.

From

According to passport data SPV-5

At 20°C ± 5°C:

In Uzbekistan, the geographical latitude and altitude above sea level (intermediate values) have values within:

After the introduction of the designation

we have

where K is the correction coefficient for the measurement location. It is known that kinematic viscosity has no negative value, i.e.:

The liquid flow time from SPV-5 will always be greater than:

Substituting (7), we obtain:

It is known that и (when performing calculations, it is necessary to take into account the units of measurement).

Simplifying the inequalities, we have

When selecting the kinematic viscosity of the washing fluid that ensures a turbulent flow regime of the fluid in the outer space for cleaning the bottomhole from sludge, it is necessary to take into account that its value should be in the range:

After determining the dynamic shear stress (, dPa), it becomes possible to evaluate drilling fluids (in subsequent calculations, it should be noted that 1 dPa = 10 Pa).

The authors [5] assert that in the FANN viscometer, the dynamic shear stress ) in dPa is calculated using the formula:

Accordingly, plastic viscosity

where and are the values of the rotation angles on the viscometer scale at sleeve rotation frequencies of 600 and 300 mi, respectively, measured in degrees.

By substituting into inequality (10), we obtain a quadratic inequality

Solving the quadratic inequality, we have:

Introductory designation

will lead to

The authors [5] state that in the VSN-3 viscometer, the dynamic shear stress () in dPa is calculated using the formula:

when using a rotation frequency of 600 and 300 mi, deg.:

Substituting into inequality (10), we obtain a quadratic inequality

Solving the quadratic inequality, we have:

introduction, designation

will lead to

when using rotation speeds of 400 and 200 mi, degrees:

By substituting into inequality (10), we obtain a quadratic inequality

Solving the quadratic inequality, we have:

introduction, designation

will lead to

To prevent absorption and hydraulic fracturing, it is necessary to combine (3) with the obtained results. Equation of pressure balance during the movement of drilling tools in the wellbore, taking into account the stability of rocks in the wellbore [8]:

where is the hydrostatic pressure, Pa; is the formation's fracture strength limit, Pa; λ is the coefficient of hydraulic resistance in the annular space; g is the acceleration of gravity, ; is the average fluid velocity in the annular space, ;

from where

Using the properties of the differential, we have

Let's integrate the result:

and let

then we have

from where

or

The combination of the model given in [8] (or (12)) and condition (3) represents a mathematical model for preventing water rupture.

Combining the hydraulic fracture model with the obtained results will allow for the construction of a complete mathematical model of the criteria and parameters of the flushing fluid to ensure the turbulent flow regime of the fluid in the annulus space.

**CONCLUSIONS**

This study examined and mathematically formulated the criteria and parameters of drilling fluid necessary to ensure effective cuttings removal during drilling operations in the geological conditions of Uzbekistan, with a focus on the transition from laminar to turbulent flow regime in the annular space. The main results and conclusions obtained in this work are as follows: The condition for determining the minimum density of drilling fluid has been refined based on two key requirements: preventing the inflow of formation fluids and preventing formation fracturing. Numerical boundaries were determined for selecting the calculation formula (2) depending on the depth of the formation top and formation pressure. Conditions for the transition to turbulent flow regime for viscoplastic fluids in the annular space have been established. A comparative analysis of Reynolds numbers in pipes and in the annular space showed that , and, consequently, the condition for ensuring a turbulent regime is

the key inequality for kinematic viscosity was obtained, which ensures a turbulent flow regime in the annulus space depending on the density, dynamic shear stress, and the well's geometric parameters (11). a complete mathematical model (13) has been developed, which combines:

- geological and technological criteria for selecting the density of the washing fluid;

- rheological criteria for ensuring turbulent flow regime;

- conditions for preventing hydraulic fracturing during the movement of drilling tools.

The proposed criterion inequalities allow for the prompt and justified selection of optimal parameters of the flushing fluid, which is an important condition for increasing the mechanical speed of drilling and reducing accidents in the complex mining and geological conditions of Uzbekistan.

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