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ОДНА ИЗ ПРИЧИН ЗАКЛИНИВАНИЯ ТРУБЫ ПРИ БУРЕНИИ

ONE OF THE REASONS OF STUCK PİPE WHILE DRILLING

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Аннотация. Опыт бурения нефтяных и газовых скважин показывает, что одним из наиболее распространенных осложнений, возникающих в процессе бурения, является заклинивание трубы. Ученые и специалисты по бурению объясняют и доказывают возникновение таких случаев по разным причинам. На самом деле, эти причины очень разные. Принимая во внимание новую физическую модель многофазного течения и реологические свойства, остро стоит вопрос оценки механических частиц (обломков) в результате дислокации (перемещения) вдоль оси цилиндрического потока из-за взаимодействия фаз в буровом растворе как фактора, вызывающего сжатие и застревание труба была рассмотрена в статье..

Ключевые слова: буровые растворы, градиент давления, вязкопластичность, напряжение сдвига, застрявшая труба.

Annotation. The experience of drilling oil and gas wells shows that one of the most common complications that occur in the drilling process is the stuck pipe. Scientists and drilling experts explain and prove the occurrence of such cases for various reasons. Indeed, these reasons are very different. Taking into account the new physical model of multiphase flow and rheological properties, the issue of evaluation of the mechanical particles (debris) as a result of the dislocation (movement) along the axis of the cylindrical flowbecause of the interaction of the phases in the drilling fluid as a factor causing compression and stuck pipe was considered in the article.

Keywords: drilling fluids, pressure gradient, visco-plastic, shear stress, stuck pipe.

Introduction

As it is known, oil and gas extraction, gathering, transportation to processing sites, separation, as well as oil, gas, formation water and mechanical particle cleaning processes are based on multiphase technologies.

It is known that the process of drilling oil and gas wells is carried out with the participation of drilling fluid, and this fluid performs several important functions. Thus, during drilling, it constantly circulates and brings the drilled rock fragments to the surface, which is one of its main functions. At this time, there are horizontal, up-bottom and bottom-up movements of the drilling fluid in laminar mode. Based on a large number of rheological studies, it was determined that drilling fluids are mainly described by a viscoplastic (pseudoplastic) rheological model [1 ÷ 4].

The movement of the drilling fluid, which has visco-plastic properties, settled in the pipe was studied by us.

It is known that the following dependence is used for the rheological description of visco-plastic fluids (Shvedov-Bingham model):

$$\tau = \tau_0 + \mu \frac{dv}{dr}, \tag{1}$$

μ – plastic viscosity; v – flow velocity.

It is typical for visco-plastic flows that they have the initial shear stress τ_0 [4, 5, 6]. At values greater than this tension, the structure of the liquid begins to disintegrate. After a certain critical velocity, the dependence $\tau = f(\gamma')$ turns into a linear dependence, and the motion of the fluid is characterized by plastic viscosity, being the motion of a Newtonian fluid ($\mu = tg\beta$). The dynamic shear stress – yield point (τ_d) is determined by extending the linear part of the dependence until it intersects the ordinate axis. It should also be noted that yield point cannot be determined experimentally.Unlike the dynamic viscosity coefficient, the plastic (structural) viscosity coefficient (μ) does not have a constant value for most fluids. As a rule, for non-Newtonian fluids, the concept of effective viscosity at a certain shear rate is used. This viscosity is calculated based on the tangent of the slope angle as a function of the shear rate ($\mu = tg\alpha$). The analysis shows that most of the fluids with visco-plastic properties show a decrease in viscosity with increasing shear rate.

The shear stress distribution along the cross-section and the yield point can be determined according to the following known expressions:

$$\tau = \frac{\Delta P * r}{2l};\ \tau_0 = \frac{\Delta P * r_0}{2l}, \qquad (2)$$

ΔP – is the pressure difference.

The tangential stress on the pipe wall (when $r = R$) takes a maximum value..

$$\tau = \tau_{max} = \frac{\Delta P * R}{2l},$$

$\tau = 0$ when $r = 0$ on the pipe axis. $\tau = \tau_0$ and $dv/dr = 0$ on a cylindrical surface with radius $r = r_0$ from the pipe axis. In the interval $0 \le r \le r_0$, the velocity of the flow remains constant, in other words, the cylindrical part with the radius r_0 moves like a solid body and is considered the core of this flow. The radius of the core is found from the following equation based on the condition $\tau = \tau_0$:

$$r_0 = \frac{2l * \tau_0}{\Delta P}.$$

According to the last condition, $\tau > \tau_0$ should be on the inner surface of the tube for the fluid to move. When $r = R$, the initial pressure difference (ΔP_0) corresponding to the stationary state of the fluid ($\tau = \tau_0$) will be as follows:

$$\Delta P_0 = \frac{2l * \tau_0}{R}.$$

That is, it is important to have the condition $\Delta P > \Delta P_0$ for the fluid to move in the pipe.

Let's examine how the gradient-velocity field changes during laminar flow of non-Newtonian drilling fluid. For this purpose, let's examine how the velocity and pressure gradient change along the cross-section of the pipe.

It is known that the change of the pressure gradient along the cross-section can be determined by the following mathematical equation [5, 6]:

$$\frac{dP}{dr} = \rho v \frac{dv}{dr}. \qquad (3)$$

Here ρ – density of drilling fluid.

Let's assume that the change in velocity (v) during the flow of the drilling fluid in the pipe occurs with the following expression:

$$v = Ar^2 + Br + C. \qquad (4)$$

Let us use the following boundary conditions to determine the coefficients A, B and C included in the trinomial (4):

When $r = R$, velocity $v = 0$ at the pipe wall is assumed.

$$Ar^2 + Br + C = 0,$$

$$\frac{dv}{dr} = 0 \text{ when } r = r_0,$$

$$\frac{dv}{dr}_{r=r_0} = 2Ar_0 + B,$$

$$\tau_{\max} = \mu \frac{dv}{dr}_{r=R} + \tau_0,$$

$$\tau_{\max} = \frac{\Delta P * r}{2l};\ \tau_0 = \frac{\Delta P * r_0}{2l}.$$

Using the mentioned conditions above, we get the following expressions for determining the coefficients A, B, C included in equation (4):

$$\left.\begin{array}{r} A = -\dfrac{\Delta P}{4\mu l} \\ B = \dfrac{\Delta P r_0}{4\mu l} \\ C = \dfrac{\Delta P R^2}{4\mu} - \dfrac{\Delta P r_0}{2\mu l} \end{array}\right\} \quad . \tag{5}$$

From the last expressions, taking into account the coefficients A, B, C, the following expression can be written for the determination of the distribution of the velocity along the cross-section of the pipe:

$$v = \frac{\Delta P}{4\mu l}(R^2 - r^2) - \frac{\tau_0}{\mu}(R - r)\ . \tag{6}$$

According to expression (6), the change of the velocity gradient along the cross-section is as follows:

$$\frac{dv}{dr} = \frac{\Delta P(r_0 - r)}{2\mu l}. \tag{7}$$

If we consider the expressions characterizing the distribution of velocity and velocity gradient (6) and (7) and the expression of τ_0 in equation (3), we get the following expression reflecting the distribution of the pressure gradient along the cross-section:

$$\frac{dP}{dr} = \frac{\rho \Delta P^2}{4\mu^2 l^2}(r - r_0)[2r_0(R - r) - (R^2 - r^2)]\ . \tag{8}$$

Considering that the expression (6) reflecting the cross-sectional velocity distribution of visco-plastic fluids during laminar flow is true only in the interval $r_0 \le r \le R$, then when $r = r_c$, as can be seen from the expression (8), the pressure gradient becomes 0 $\frac{\Delta P}{\Delta r} = 0$. By the same rule, when r = R, that is, the pressure gradient on the pipe wall is equal to 0 ($\frac{\Delta P}{\Delta r} = 0$) and in the center of the tube (when r = 0) $\frac{dP}{dr} = \frac{\rho(R - 2r_0)\tau_{max}\tau_0}{\mu^2}$.

The maximum value of the pressure gradient along the cross-section can be determined by deriving the expression (8). So, if we take the derivative of that expression with respect to r and make it equal to zero, we get the following quadratic equation:

$$3r^2 - 6r_0 r + (2r_0 R - R^2 + 2{r_0}^2) = 0.$$

Following roots are obtained from the solution of the last equation with respect to r:

$$r_1 = r_0 + \frac{\sqrt{3}}{3}(R - r_0),$$

$$r_2 = r_0 - \frac{\sqrt{3}}{3}(R - r_0).$$

As you can see, although the second root satisfies the equation because $r_2 < r_0$ is obtained, it contradicts the condition $r \ge r_0$ mentioned above. Therefore, the pressure gradient dP/dr will have a maximum value at $r^* = r_0 + \frac{\sqrt{3}}{3}(R - r_0)$. This value will be as follows:

$$\frac{dP}{dr}_{\max} = \frac{\sqrt{3}\rho(R - r_0)(\tau_{\max} - \tau_0)^2}{3\mu^2}.$$

The variation of flow parameters (velocity, tangential stress, velocity gradient and pressure gradient) for visco-plastic fluids is shown in figure 1.

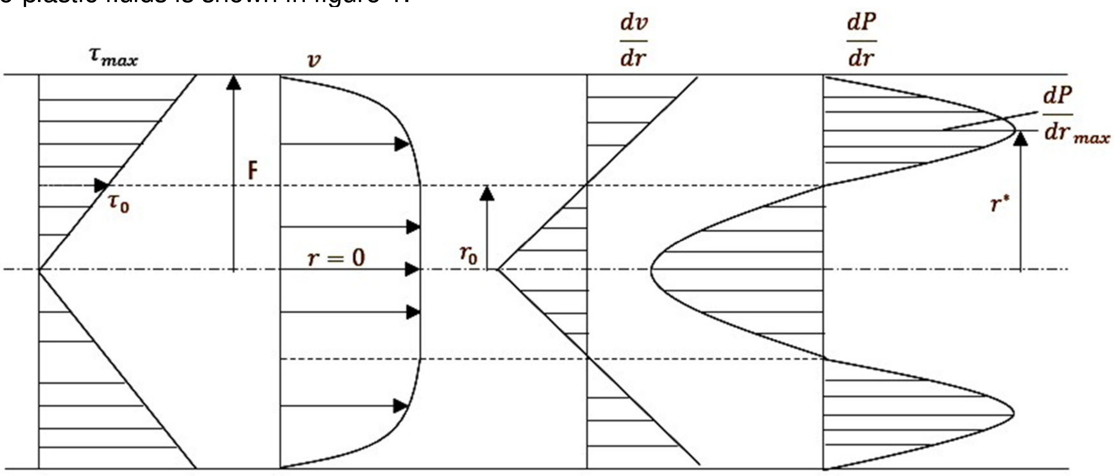

Figure1 – Cross-sectional distribution of flow parameters of visco-plastic drilling fluid

Studies show that the structure of multiphase flows (gas-liquid, oil-water-gas, oil-gas-mechanical particles, drilling fluids, etc.) is highly dependent on the orientation and direction of movement of the channel (pipe). So, during the movement of these flows in the vertical pipe from top to bottom and vice versa from bottom to top, as well as in horizontal direction, their characteristics differ significantly from each other. Although there is currently a considerable amount of scientific research work on horizontal and bottom-top vertical flows, top-bottom flow forms have been limited studied .

The results of scientific research conducted in recent years have shown that there is mutual influence of phases in multiphase cylindrical flows regardless of the direction [5 ÷ 8]. As the gradient-velocity field is formed not only along the length but also along the cross-section of the flow according to the law of conservation of energy, the continious phase is able to transport dispersed phase particles along the axis of the flow, in its center. Due to the Bernoulli force, which is directed from the edges of the cylindrical flow towards the center, those particles (mechanical, gas, water, etc.) very easily move in the core of the continious phase, being directed to the axis of the flow.

It is known that during such flows mainly gravity, Archimedes, and Bernoulli forces (if we do not consider friction and inertia forces) are active forces, which cause sedimentation and migration phenomena. It is clear that although the direction of these forces is known, their effect will be different depending on the direction of the multiphase flow. So, in vertical downward and upward flows, Archimedean and gravitational forces will be opposite to each other, and Bernoulli's force will be perpendicular to them. In the case of horizontal flows, although the direction of all three forces is perpendicular to the flow, the Bernoulli force will be perpendicular to the axis of the flow from the edges, and the Archimedean and gravitational forces will be opposite to each other. Schematically, the directions of these forces in different directional flows are shown in figure 2.

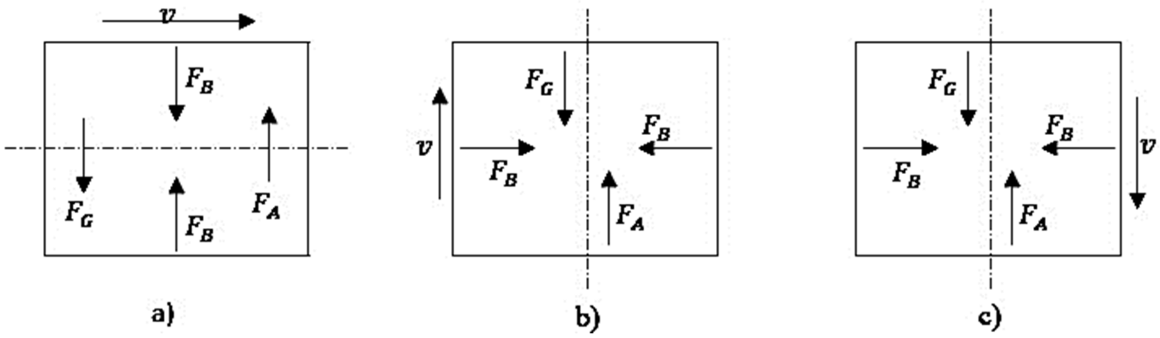

Figure 2 – Direction of active forces in multiphase flows with different directions:
a) – horizontal, b) – bottom to top, c) – top to bottom;
F_B – Bernoulli force, F_A – Archimedes force, F_G – Gravitational force

Thus, the cross-sectional transfer of matter and energy in multiphase flows does not occur only due to turbulent diffusion. This process is also caused by the directed movement of the medium itself. Such transfer phenomena, which are characteristic of multiphase flows and multicomponent drilling fluid, occur due to the Bernoulli force, which causes the interaction of phases in both horizontal and gravity flows [4, 7]:

$$F_B = 0.167\pi d^3 \frac{dP}{dr}. \tag{9}$$

Here d – the diameter of the dispersed phase particle, the volume of the particle (gas bubble, mechanical particle, scrap, etc.) with a diameter d of $0.167\pi d^3$; dP/dr – is the pressure gradient across the flow cross-section.

The transfer movement of the flow along the cross-section occurs under the influence of the pressure gradient along the length (height), against the background of the movement of the medium. Turbulence of the flow also increases with the increase of the average flow rate, because the pressure gradient along the cross-section increases more intensively with the increase of the velocity.

If we consider the expression that reflects the change of expressions of pressure gradient, v and dv/dr, in equation (9) we get:

$$F_B = 0.167\pi d^3(\rho_{m.h} - \rho_m)g\ . \tag{10}$$

As can be seen from the last statement, the Bernoulli force directed from the pipe wall to the center of the flow in the cylindrical flow increases significantly as the density difference of the mechanical particles and fluid (drilling fluid) and the diameter of the mechanical cuttings increase.

As can be seen from the last expression, the migration of the dispersed phase to the center of the flow is inevitable despite the high degree of dispersion even in the small diameters of the rock fragments. Therefore, due to intensive migration (transportation) of drilled rock particles to the center of the flow due to the effect of the Bernoulli force caused by the variable pressure gradient, it can greatly increase the local resistance caused by friction and cause the stuck pipe.

Conclusions

Based on the physical model of multiphase cylindrical flows, the regularity of the formation of the velocity-gradient field during its movement in the pipe, taking into account the visco-plastic properties of the drilling fluid, has been shown.

It has been shown that one of the possible causes of stuck pipe during drilling of oil and gas wells is due to the compression of the tool as a result of the dislocation of mechanical particles and rock fragments in the direction of the flow axis due to the Bernoulli force formed by the velocity-gradient field.

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