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Determination of dynamic formation pressure in the wellbore zone

Wyznaczanie dynamicznego ciśnienia formacji w strefie odwiertu

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ABSTRACT: The article shows that the pressure drop in the near-wellbore zone decreases with increasing time that the well is left uncased due to the filtration of the drilling fluid filtrate into the formation. Under certain conditions, this does not pose a risk of drill string sticking. From the perspective of establishing the nature of changes in dynamic reservoir pressure behind the mud cake, the experimental studies by Johnson and Klotz (Stepanov, 1999), which determine the amount of filtrate entering the reservoir under both static and dynamic conditions, are particularly interesting. It should be noted that establishing the amount of filtrate experimentally takes into account in advance the nonlinearity of fluid movement along the borehole wall and through formation rocks. Reservoir pressure will increase to the depth of penetration of the drilling fluid filtrate, so the value of R_k is taken equal to the radius of a certain contour with formation pressure. The article shows that the dynamic reservoir pressure behind the mud cake initially rises intensively over time, and then, after a certain point, remains almost constant; the filtrate from the drilling fluid entering the formation partially displaces the reservoir fluid and fills the resulting pore space. During dynamic filtration, an intensive increase in pressure behind the mud cake occurs within 20–30 hours and depends little on the absolute values of fluid loss from the washing liquid, the thickness of the mud cake, and the initial pressure drop. Experience in drilling deep wells shows that sticking of the lower part of the drill string primarily occurs when opening productive horizons with low permeability $(0.06^{-2}) \cdot 10^{-15}$ m^2. Consequently, the ratio of the permeability of the rock of deep-lying productive horizons to that of the mud cake is approximately more than 1,000. Therefore, when opening productive horizons, pressure equalization practically does not occur, and leaving the drill string against these rock formations without movement for 15–20 minutes leads to its sticking due to the pressure difference.

Key words: drilling fluid, sticking, well pressure, wellbore axis, Darcy equations, filtrate, fluid loss, mud cake.

STRESZCZENIE: W artykule wykazano, że spadek ciśnienia w strefie przyodwiertowej zmniejsza się wraz z wydłużeniem czasu, w którym odwiert pozostaje niezarurowany, ze względu na przenikanie filtratu płuczki wiertniczej do formacji. W określonych warunkach nie stwarza to ryzyka zakleszczenia przewodu wiertniczego. Z punktu widzenia ustalenia charakteru zmian ciśnienia dynamicznego w złożu poza osadem płuczkowym, szczególnie interesujące są badania eksperymentalne Johnsona i Klotza (Stepanov, 1999), które określają ilość filtratu przedostającego się do złoża zarówno w warunkach statycznych, jak i dynamicznych. Należy zauważyć, że ustalając ilość filtratu eksperymentalnie, z góry zakłada się nieliniowość ruchu płynu wzdłuż ściany odwiertu i przez skały formacji. Ciśnienie złożowe będzie wzrastać do głębokości penetracji filtratu płuczki wiertniczej, dlatego wartość R_k przyjmuje się jako równą promieniowi danego konturu przy ciśnieniu złożowym. W artykule wykazano, że dynamiczne ciśnienie złożowe za osadem płuczkowym początkowo intensywnie rośnie w czasie, a następnie, po pewnym czasie, pozostaje prawie stałe; filtrat z z płuczki wiertniczej wpływający do formacji częściowo wypiera płyn złożowy i wypełnia powstałą przestrzeń porową. Podczas filtracji dynamicznej intensywny wzrost ciśnienia za osadem płuczkowym następuje w ciągu 20–30 godzin i zależy w niewielkim stopniu od bezwzględnych wartości utraty płuczki, grubości osadu płuczkowego i początkowego spadku ciśnienia. Doświadczenie w wierceniu głębokich odwiertów pokazuje, że zakleszczenie dolnej części przewodu wiertniczego występuje głównie podczas wiercenia horyzontów produkcyjnych o niskiej przepuszczalności $(0,06^{-2}) \cdot 10^{-15}$ m^2. W związku z tym stosunek przepuszczalności skał głęboko położonych horyzontów produkcyjnych do przepuszczalności osadu płuczkowego wynosi w przybliżeniu ponad 1000. Dlatego podczas przewiercania poziomów złożowych praktycznie nie występuje wyrównanie ciśnienia, a pozostawienie przewodu wiertniczego w tych formacjach bez ruchu przez 15–20 minut prowadzi do jego zakleszczenia z powodu różnicy ciśnień.

Słowa kluczowe: płuczka wiertnicza, zakleszczanie, ciśnienie w odwiercie, oś odwiertu, równania Darcy'ego, filtrat, utrata płuczki, osad płuczkowy.

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Introduction

Theoretical and experimental studies have shown that the pressure drop in the near-wellbore zone decreases over time when the wellbore is left open due to the filtration of the drilling fluid filtrate into the formation. Under certain conditions, this does not pose a risk of drill string sticking.

From the perspective of establishing the nature of changes in dynamic reservoir pressure behind the mud cake, the experimental studies by Johnson and Klotz (Stepanov, 1999), which determine the amount of filtrate entering the reservoir both under static and dynamic conditions, are particularly interesting. It should be noted that establishing the amount of filtrate experimentally takes into account in advance the nonlinearity of fluid movement along the borehole wall and through formation rocks (Sailov et al. 1996; Stepanov, 1999). This phenomenon is characterized by the degree of pressure equalization:

$$\beta = 1 - (p_1 - p_c)$$

where:

p_c – pressure in the well,

p_1 – average pressure in the mud cake.

It can be assumed that, as a result of filtration, the pressure in the near-wellbore zone is distributed as follows: in the well – p_1, behind the mud cake – p_δ, at distances – r and R_k from the axis of the wellbore – p_r and p_k (Figure 1).

Materials and methods

The problem of pressure distribution in the wellbore zone can be reduced to solving the Darcy equation under radial filtration conditions (Travkin, 1992; Pontryatev et al., 1993):

$$dp = \frac{q\mu}{2\pi hK}\frac{dr}{r} \tag{1}$$

Solving (1) taking into account filtration conditions in media of different permeability, we can determine the dynamic reservoir pressure (or pressure drop) in the near-wellbore zone:

$$p_r = p_1 - \frac{\Delta p}{\dfrac{\ln\left(R_k/r\right)}{\left(K_p/K_k\right)\ln\left(R_c/(R_c-\delta)\right)+\ln\left(r/R_c\right)}} \tag{2}$$

where:

Δp – initial pressure drop between the well and the formation [MPa],

K_p/K_k – permeability of rock and mud cake,

R_c – well radius,

δ – well wall thickness.

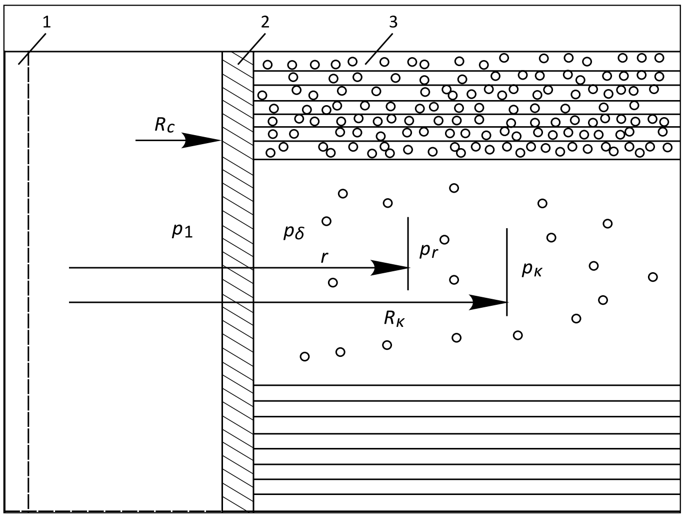

Figure 1. Calculation scheme for determining pressures in the near-wellbore zone of wells being drilled: 1 – well; 2 – mud cake; 3 – formation layer

Rysunek 1. Schemat obliczeniowy do określania ciśnień w strefie przyodwiertowej otworów w trakcie wiercenia: 1 – odwiert; 2 – osad płuczkowy; 3 – warstwa formacji skalnej

The reservoir pressure will increase to the depth of penetration of the drilling fluid filtrate, so the value of R_k is taken as equal to the radius of a certain contour with formation pressure (Terentyev and Mikhailenko, 1992).

The filtrate from the drilling fluid entering the formation (while the well is left uncased) will partially displace the formation fluid and fill the resulting pore space. Then the penetration depth of the filtrate, assumed to be equal to R_k, can be determined from the equation:

$$\Phi = \pi\left(R_k^2 - R_c^2\right)m\alpha \tag{3}$$

where:

Φ – amount of liquid filtered into the formation, m^3 per 1 m well interval,

m – formation porosity,

α – coefficient of residual saturation of the formation with liquid.

Solving equation (3) for R_κ, we get:

$$R_\kappa = \sqrt{(\Phi / m\alpha) + R_c^2} \tag{4}$$

During the drilling process, both dynamic (in the presence of solution circulation) and static (in the absence of circulation) filtration into the formation occurs (Basniev et al, 1999; Aliev, 2005).

The amount of liquid filtered into the formation F during static Φ_s and dynamic Φ_d filtration is calculated using the following formulas:

$$\Phi_s = 1.01\cdot10^{-5}BD\alpha_{ts}\cdot\Delta p^{0.2}t_s\sqrt{t_s} \tag{5}$$

$$\Phi_d = 3.48\cdot10^{-5}BD\alpha_{td}\cdot\Delta p^{0.2}t_d\sqrt{Q/M^3} \tag{6}$$

where:
B – water loss of flushing fluid for 0,5 hours by BM-6 [m^3/h],
D – well diameter [m],
α_{ts} and α_{td} – temperature coefficient of static and dynamic filtration,
Q – pump supply [m^3/h],
M – hydraulic radius of the annulus [m].

In terms of drill string sticking, which occurs under the influence of a pressure difference, it is useful to determine the pattern of pressure changes behind the mud cake p_δ. By substituting $r = R_c$ into (2) and using formulas (4), (5) and (6) to determine p_δ under conditions of static and dynamic filtration, we obtain:

$$p_{\delta 1} = p_1 - \frac{\Delta p}{1 + \ln \sqrt{1 + \frac{0.064 \alpha_{tc} B \cdot \Delta p^{0.2} t_c \sqrt{Q / M^3}}{\alpha m R_c}} / \frac{K_p}{K_k} \ln \frac{R_c}{R_c^{-8}}} \quad (7)$$

$$p_{\delta 2} = p_1 - \frac{\Delta p}{1 + \ln \sqrt{1 + \frac{0.22 \alpha_{td} B \cdot \Delta p^{0.2} t_d \sqrt{Q / M^3}}{\alpha m R_c}} / \frac{K_p}{K_k} \ln \frac{R_c}{R_c^{-8}}} \quad (8)$$

Figures 2 and 3 show, as an example, the change in dynamic reservoir pressure over time with dynamic (curves 1–3) and static (curve 4) filtration under the following conditions: diameter of drill pipes $d_н = 0.141$ m; $\alpha = 0.5$, $m = 0.2$, $\delta = 0.002$ m, $Q = 9$ m^3/h, $K_p/K_k = 20$, $p_1 = 50$ MPa, $p_r = 30$ MPa. As can be seen from these figures, the value of the dynamic reservoir pressure behind the mud cake initially increases rapidly over time, and then, after a certain time, remains almost constant.

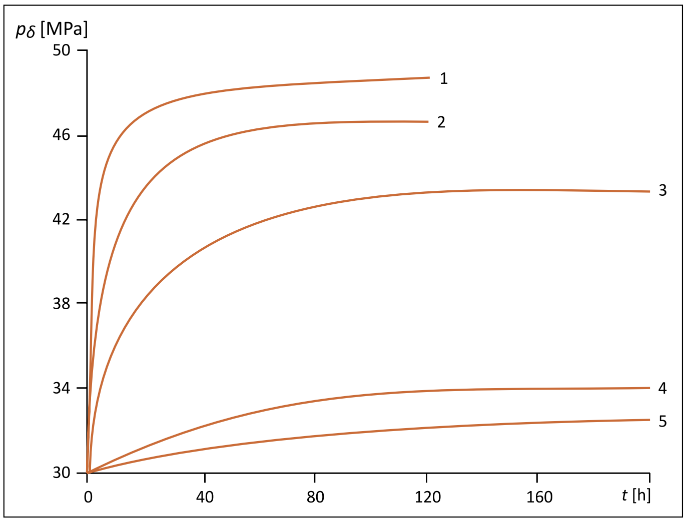

Figure 3. Dependence of dynamic reservoir pressure on time for various filtration characteristics of rock and mud cake: 1, 2, 3, 4 – K_pK^* respectively 10, 30, 100 and 1000 (dynamic filtering); 5 – $K_pK_t = 1000$ (static filtering)

Rysunek 3. Zależność dynamicznego ciśnienia złożowego od czasu dla różnych charakterystyk filtracji skał i osadu płuczkowego: 1, 2, 3, 4 – K_pK^* odpowiednio 10, 30, 100 oraz 1000 (filtracja dynamiczna); 5 – $K_pK_t = 1000$ (filtracja statyczna)

During dynamic filtration, an intensive increase in pressure behind the mud cake occurs within 20–30 hours and depends little on the absolute values of fluid loss from the washing liquid, the thickness of the mud cake, and the initial value of the pressure drop (Sherrard, 1993; Gritsenko et al, 1995).

The intensity of the increase in dynamic reservoir pressure behind the mud cake over time mainly depends on the ratio of the permeability of the rock and the mudcake K_p/K_k.

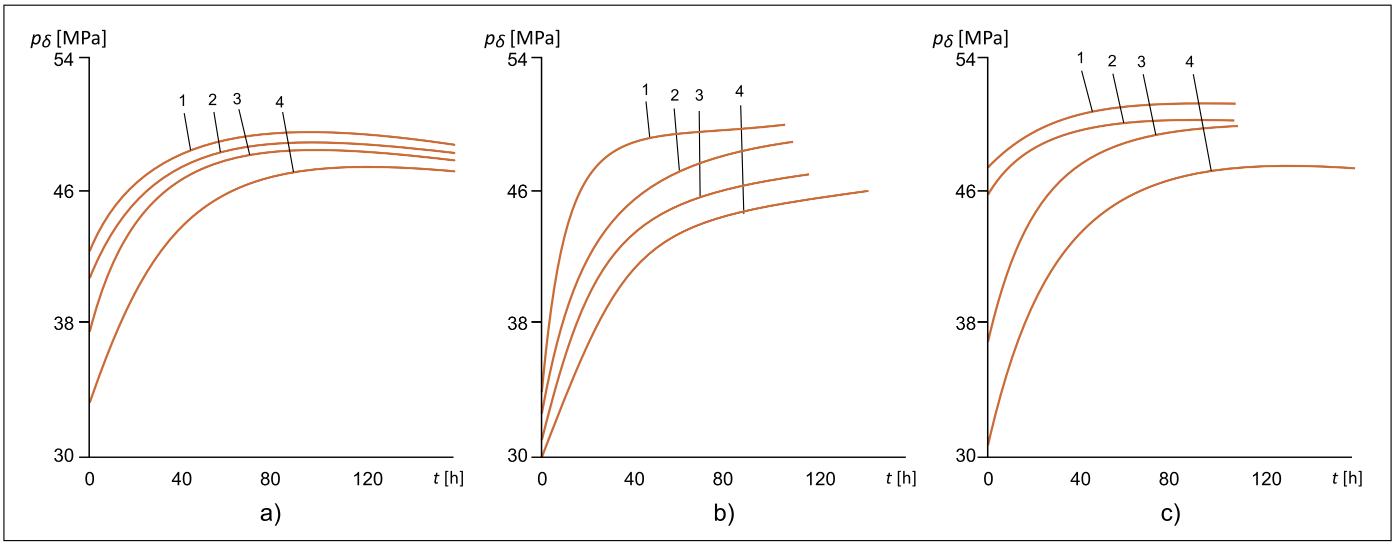

Figure 2. Changes in reservoir dynamic pressure over time: a) 1 – $B = 10 \cdot 10^3$ m^3, 2 – $B = 5 \cdot 10$ m^3, 3, 4 – $B = 3 \cdot 10^3$ m^3; b) 3 – $B = 1 \cdot 10^3$ m^3, 2 – $B = 2 \cdot 10^3$ m^3, 3, 4 – $B = 3 \cdot 10^3$ m^3; c) 1 – $p_k = 45$ MPa, 2 – $p_k = 40$ MPa, 3, 4 – $p_k = 30$ MPa

Rysunek 2. Zmiany ciśnienia dynamicznego w złożu w czasie: a) 1 – $B = 10 \cdot 10^3$ m^3, 2 – $B = 5 \cdot 10$ m^3, 3, 4 – $B = 3 \cdot 10^3$ m^3; b) 3 – $B = 1 \cdot 10^3$ m^3, 2 – $B = 2 \cdot 10^3$ m^3, 3, 4 – $B = 3 \cdot 10^3$ m^3; c) 1 – $p_k = 45$ MPa. 2 – $p_k = 40$ MPa, 3, 4 – $p_k = 30$ MPa

Figure 3 shows the nature of the change in dynamic reservoir pressure behind the mud cake over time at different values of K_p/K_k. At K_p/K_k =10 (curve 1), the pressure drop in the mud cake within 20 hours decreases from 20 to 15 MPa and subsequently remains almost constant, and at K_p/K_k = 1000 (curve 4), the pressure drop over 110 hours decreases only by 4 MPa.

Conclusions

Experience in drilling deep wells indicates that sticking of the lower part of the drill string occurs primarily when opening productive horizons with low permeability $(0.06^{-2}) \cdot 10^{-15}$ m^2. Consequently, the ratio of the permeability of the rock of deep-lying productive horizons and that of the mud cake is approximately above 1,000. Therefore, when opening productive horizons, pressure equalization rarely occurs. If the drill string is left against these rocks without movement for 15–20 minutes, it may become stuck due to resulting pressure difference.

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