Archives of Mining Sciences 48, 1 (2003) 119–131

CZESŁAW RYBICKI*, JACEK BLICHARSKI**

ASSESSMENT OF NEAR-WELL ZONE DAMAGING DURING GAS-WELL RECONSTRUCTION PROCEDURES

OCENA STOPNIA USZKODZENIA STREFY PRZYODWIERTOWEJ PODCZAS REKONSTRUKCJI ODWIERTÓW GAZOWYCH

Issues related to gas wells reconstruction are discussed in this paper. The extent to which the near-well zone is damaged by drilling mud during reconstruction procedures, is assessed on the basis of a simple mathematical model. It follows from the analysis that the main causes of damage are reservoir rock itself, properties of the mud, repression and duration of the whole process.

Key words: solid filter cake, formation zone, fluid penetration, flow of fluid, mud filtration, drainage zone, damage zone, reservoir

Jednym z istotnych problemów związanych z zabiegami rekonstrukcji odwiertów ropnych i gazowych jest niebezpieczeństwo wnikania płuczki do strefy przyodwiertowej, co często powoduje nieodwracalne skutki w postaci zmniejszenia lub czasami zaniku dopływu gazu lub ropy do odwiertu. Istotne jest zatem dobre rozeznanie zjawiska filtracji płynów zabiegowych, takich jak: płuczka wiertnicza, woda, ciecze szczelinujące i kwasujące oraz inne do ośrodka porowatego. Stosowane płyny zabiegowe zarówno w procesie wiercenia jak też rekonstrukcji odwiertów zawierają fazę stałą w postaci cząsteczek, które mogą wnikać w strukturę porową złoża zmniejszając tym samym jego przepuszczalność.

Stopień i intensywność wnikania cząstek stałych do skały oraz osadzania się ich na powierzchni skały (ściance odwiertu) zależy od struktury przestrzeni porowej skały, wymiarów porów, jak też wymiarów i kształtów wnikających cząstek. Na wielkość strefy objętej wnikaniem cząstek duży wpływ ma również stopień zeszczelinowania złoża, istnienie szczelin prowadzi bowiem często do głębokiej penetracji i skażenia dużej części skały złożowej wokół odwiertu.

W artykule dokonano analizy problemów związanych z rekonstrukcją odwiertów gazowych. W oparciu o prosty model matematyczny dokonana została ocena stopnia uszkodzenia strefy przy-

* WYDZIAŁ WIERTNICTWA NAFTY I GAZU, AKADEMIA GÓRNICZO-HUTNICZA, AL. MICKIEWICZA 30, 30-059 KRAKÓW, tel.: (+48 12) 617 20 85, POLAND; e-mail: rybicki@uci.agh.edu.pl
** WYDZIAŁ WIERTNICTWA NAFTY I GAZU, AKADEMIA GÓRNICZO-HUTNICZA, AL. MICKIEWICZA 30, 30-059 KRAKÓW, tel.: (+48 12) 617 20 85, POLAND; e-mail: jblich@uci.agh.edu.pl

odwiertowej przez użytą płuczkę podczas zabiegów rekonstrukcyjnych. Zaadaptowany został model dopływu płynu do odwiertu przy stałej różnicy ciśnień dla przypadku filtracji płuczki w złoże. Założono stałą różnicę ciśnień pomiędzy ciśnieniem hydrostatyczny słupa płuczki w odwiercie a ciśnieniem złożowym. W oparciu o ten model autorzy przeprowadzili obliczenia zmian parametrów strefy przyodwiertowej w przypadku filtracji płuczki w skałę złożową. Określone zostały takie wielkości, jak: zasięg strefy filtracji płynu zabiegowego, skin efekt, stopień zmiany przepuszczalności średniej ośrodka porowatego oraz ilość płynu zabiegowego wnikającego do złoża w czasie trwania zabiegu.

Z przeprowadzonej analizy wyników obliczeń przedstawionych graficznie wynika, że zasadniczy wpływ na uszkodzenie strefy przyodwiertowej mają: własności skały złożowej, własności użytej płuczki, wielkość represji ciśnienia oraz czas trwania zabiegu.

Słowa kluczowe: filtracja płynu, adsorpcja, struktura porowa, przepuszczalność osadu z cząstek stałych, wydatek wnikającego filtratu, uszkodzenie strefy przyodwiertowej, strefa drenażu, złoże

1. Introduction

One of the most important problems related to oil and gas well reconstruction is the possibility of mud penetration in the near-well zone. This may often create irreperable changes in the form of lowering or vanishing of oil or gas influxes to the well. Therefore, it is advisable to well recognize the filtration of such fluids as mud, water, fracturing and acidifying fluids in the porous medium. The fluids, used during drilling and reconstructing works, contain some portion of solids in the form of particles able to penetrate the porous structure of the deposit, lowering its permeability (Herman at al. 2002; Dubiel at al. 2001).

The degree and intensity of solids penetration into the rock and their sedimentation abilities (on the well's walls) depends on the porous structure of the rock, size of the pores, as well as the size and shape of the penetrating particles. The size of the zone subjected to particle penetration is also conditioned by the degree to which the reservoir is fractured. Fractures often lead to a very deep penetration and contamination of a vast part of the deposit in the near well zone.

2. Model of solid filter cake formation and behaviour

Hydrostatic pressure of fluids of a given density changes with depth. When hydrostatic pressure is higher than formation pressure, fluid filtrates to the formation. Depending on the size of solids and pore canals, the particles may either migrate inside the rock or be deposited on the well's wall. Particles having diameter smaller than the diameter of pore canals, penetrate the porous medium (Fig. 1), whereas particles having diameter bigger than pore canals form filter cake on the well's wall (Fig. 2).

Low permeability of filter cake prevents further penetration of solid particles into the deposit. In the static conditions, at zero mud circulation, the thickness of filter cake increases with time of reconstruction procedures. In the dynamic conditions, the thickness of the filter cake depends on difference between the rate of sedimentation due

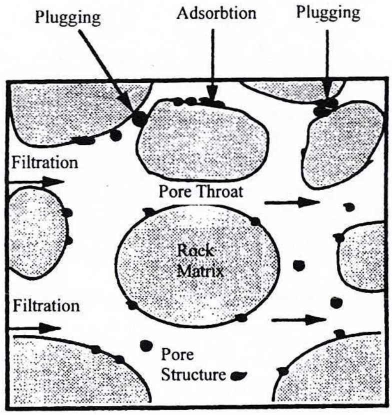

Fig. 1. Filter cake settling on the inner surface of rock

Rys. 1. Mechanizm osadzania się cząsteczek stałych na wewnętrznej powierzchni skały

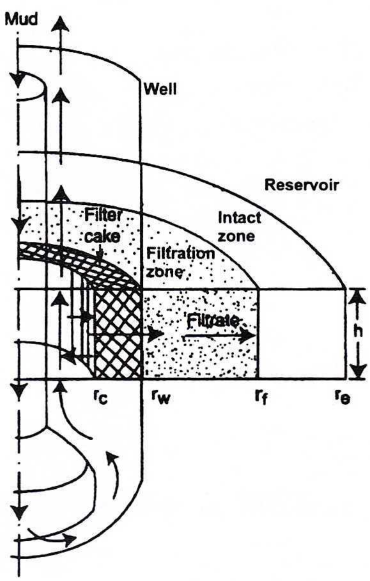

Fig. 2. Filter cake formation

Rys. 2. Powstawanie osadu z cząstek stałych na ściance odwiertu

to filtration processes and erosion of the filter cake caused by the mud flow. Filter cake formed on the well's wall is also porous and permeable, but its parameters depend on pressure gradients, influencing compressive strength of the cake. When the mud is a water-based colloid suspension, the mathematical description of the process of filter cake deposition on a well's wall can be expressed by the following formula (Civan 1999):

$$\frac{d\delta}{dt} = A \cdot w - B \tag{1}$$

$$w = \frac{q}{2 \cdot \pi \cdot h \cdot r_c} \tag{2}$$

where:

$r_c = r_w - \delta$ — radius of solid filter cake (Fig. 2)
δ — thickness of solid filter cake,
q — rate of filtrate penetration,

A and B are expressed by the formulae:

$$A = \frac{k_d \cdot c_p}{(1 - \phi_c) \cdot \rho_p} \tag{3}$$

where:

c_p — mass concentration of solids in mud,
k_d — filter cake deposition factor,
ϕ_c — porosity of solid filter cake,
ρ_p — density of solids.

and

$$B = \varepsilon \cdot (\tau_s - \tau_{kr}) \cdot U(\tau_s - \tau_{kr}) \cdot H(\delta) \tag{4}$$

where:

ε — filtration cake erosion,
τ_s — shearing stress,
τ_{kr} — critical shearing stress.

The functions $U(\tau_s - \tau_{kr})$ and $H(\delta)$ in equation (4) are conditional functions assuming the respective values:

$$U(\tau_s - \tau_{kr}) = 0 \quad \text{for} \quad \tau_s < \tau_{kr}$$

or

$$U(\tau_s - \tau_{kr}) = 1 \quad \text{for} \quad \tau_s > \tau_{kr}$$

and

$$H(\delta) = 0 \quad \text{for} \quad \delta = 0$$

or

$$H(\delta) = 1 \quad \text{for} \quad \delta > 0$$

In industrial conditions, means reducing fluids penetration into the rock are applied. They are called blockers. For further considerations, radius r_c will denote the inner radius of cake zone formed by fluids filtration or by an artificial use of a blocker.

The process of filtrate penetration into the deposit at a radial uni-phase flow, can be expressed by the following Forcheimer's filtration equation in the form:

$$-\frac{\partial p}{\partial r} = \frac{\mu}{k} \cdot w + \overline{\beta} \cdot \rho \cdot w^2 \tag{5}$$

For small filtration rates equation (5) assumes the form of Darcy's equation Equation (5) uses the relation (2), which can be rewritten as:

$$-\frac{\partial p}{\partial r} = \frac{\mu}{k} \cdot \frac{q}{2 \cdot \pi \cdot h \cdot r} + \overline{\beta} \cdot \rho \cdot \left(\frac{q}{2 \cdot \pi \cdot h \cdot r_c} \right)^2 \tag{6}$$

Assuming that fluid penetration takes place from the intact zone having permeability k limited with radii r_c and r_e in radial conditions, equation (6) assumes the form:

$$p_c - p_e = \frac{q_o \cdot \mu}{2 \cdot \pi \cdot k \cdot h} \cdot \ln\left(\frac{r_e}{r_c} \right) + \frac{\rho \cdot \beta \cdot q_o^2}{(2 \cdot \pi \cdot h)^2} \cdot \left(\frac{1}{r_c} - \frac{1}{r_e} \right) \tag{7}$$

where:

q_o — rate of fluid penetrating intact zone.

Actually, fluid filtration takes place through three zones: solid cake zone, zone covered by filtrate, and zone of intact rock-mass. Therefore, equation (7) assumes the following form:

$$p_c - p_e = \frac{q \cdot \mu}{2 \cdot \pi \cdot \overline{k} \cdot h} \cdot \ln\left(\frac{r_e}{r_c} \right) + \frac{\rho \cdot \overline{\beta} \cdot q^2}{(2 \cdot \pi \cdot h)^2} \cdot \left(\frac{1}{r_c} - \frac{1}{r_e} \right) \tag{8}$$

where:

q — rate of penetrating fluid, accounting for zones of different permeability.
$\overline{k}$ — mean permeability for the zone of filter cake, filtrate, intact rock-mass. It is expressed by the following relation:

$$\overline{k} = \frac{\ln \frac{r_e}{r_c}}{\frac{\ln \frac{r_w}{r_c}}{k_c} + \frac{\ln \frac{r_f}{r_w}}{k_f} + \frac{\ln \frac{r_e}{r_f}}{k}} \tag{9}$$

where:

r_e — radius of well's impact,
r_f — radius of zone occupied by filtrate,

r_w — well's radius,
k_c — permeability of solid filtration cake,
k_f — permeability of zone occupied by filtrate.

$\overline{\beta}$ — turbulence coefficient characteristic of the system: solid cake-zone occupied by filtrate-intact rock-mass, expressed by the following formula:

$$\overline{\beta}\cdot\left(\frac{1}{r_c}-\frac{1}{r_e}\right)=\beta_c\cdot\left(\frac{1}{r_c}-\frac{1}{r_w}\right)+\beta_f\cdot\left(\frac{1}{r_w}-\frac{1}{r_f}\right)+\beta\cdot\left(\frac{1}{r_f}-\frac{1}{r_e}\right) \tag{10}$$

where:

β_c, β_f, β — turbulence coefficient for the zones of filtrate cake, filtrate and intact rock-mass, respectively.

Using equations (9) and (10), equation (8) may be rewritten:

$$p_c-p_e=\frac{q\cdot\mu}{2\cdot\pi\cdot k\cdot h}\cdot\left[\frac{k}{k_c}\cdot\ln\left(\frac{r_w}{r_c}\right)+\frac{k}{k_f}\cdot\ln\left(\frac{r_f}{r_w}\right)+\ln\left(\frac{r_e}{r_f}\right)\right]+ \tag{11}$$

$$\frac{\rho\cdot\beta\cdot q^2}{(2\cdot\pi\cdot h)^2}\cdot\left[\frac{\beta_c}{\beta}\cdot\left(\frac{1}{r_c}-\frac{1}{r_w}\right)+\frac{\beta_f}{\beta}\cdot\left(\frac{1}{r_w}-\frac{1}{r_f}\right)+\left(\frac{1}{r_f}-\frac{1}{r_e}\right)\right]$$

Equation (11) is a sum of filtrations of solids, filtration zone and intact rock-mass.

Assuming that the flows described by equations (8) and (12) take place at the same pressure difference, the equation may be compared by sides, and the following relation is obtained:

$$\frac{q_o\cdot\mu}{2\cdot\pi\cdot k\cdot h}\cdot\ln\left(\frac{r_e}{r_c}\right)+\frac{\rho\cdot\beta\cdot q_o^2}{(2\cdot\pi\cdot h)^2}\cdot\left(\frac{1}{r_c}-\frac{1}{r_e}\right)= \tag{12}$$

$$=\frac{q\cdot\mu}{2\cdot\pi\cdot k\cdot h}\cdot\left[\frac{k}{k_c}\cdot\ln\left(\frac{r_w}{r_c}\right)+\frac{k}{k_f}\cdot\ln\left(\frac{r_f}{r_w}\right)+\ln\left(\frac{r_e}{r_f}\right)\right]+$$

$$+\frac{\rho\cdot\beta\cdot q^2}{(2\cdot\pi\cdot h)^2}\cdot\left[\frac{\beta_c}{\beta}\cdot\left(\frac{1}{r_c}-\frac{1}{r_w}\right)+\frac{\beta_f}{\beta}\cdot\left(\frac{1}{r_w}-\frac{1}{r_f}\right)+\left(\frac{1}{r_f}-\frac{1}{r_e}\right)\right]$$

Substituting to equation (12):

$$a=\frac{\rho\cdot\beta}{(2\cdot\pi\cdot h)^2}\cdot\left[\frac{\beta_c}{\beta}\cdot\left(\frac{1}{r_c}-\frac{1}{r_w}\right)+\frac{\beta_f}{\beta}\cdot\left(\frac{1}{r_w}-\frac{1}{r_f}\right)+\left(\frac{1}{r_f}-\frac{1}{r_e}\right)\right]$$

$$b = \frac{\mu}{2 \cdot \pi \cdot k \cdot h} \cdot \left[\frac{k}{k_c} \cdot \ln\left(\frac{r_w}{r_c}\right) + \frac{k}{k_f} \cdot \ln\left(\frac{r_f}{r_w}\right) + \ln\left(\frac{r_e}{r_f}\right) \right]$$

$$c = -\frac{q_o \cdot \mu}{2 \cdot \pi \cdot k \cdot h} \cdot \ln\left(\frac{r_e}{r_c}\right) + \frac{\rho \cdot \beta \cdot q_o^2}{(2 \cdot \pi \cdot h)^2} \cdot \left(\frac{1}{r_c} - \frac{1}{r_e}\right)$$

equation (12) can be rewritten:

$$a \cdot q^2 + b \cdot q - c = 0 \tag{13}$$

$$q = \frac{-b + \sqrt{b^2 - 4 \cdot a \cdot c}}{2 \cdot a} \tag{14}$$

With this equation the actual rate can be calculated, accounting for the properties of solid filter cake, filtration zone and intact rock-mass for a given rate of intact rock-mass q_o.

3. Mud filtration in a deposit at constant drop of pressure

In the well reconstruction procedures, pressure is often raised to protect the well against deposit pressure. This is done by a proper selection of density and column of mud in the well, so that the hydrostatic pressure slightly exceeds reservoir pressure. The amount of mud penetrating the deposit depends on this difference. This penetration is responsible for contamination of the near-well zone. In practice, all should be done to minimize the influence of mud filtration and guarantee that no eruption takes place.

Fluid filtration is a result of differences of bottom pressure and reservoir pressure. Assuming that the well pressure is related with a definite column, which will be constant for a certain time, filtration will continue at a constant drop of pressure. Therefore, assuming a constant drop of pressure, the cumulative rate of such an influx can be described by the following equation (Slider 1983):

$$Q = 2 \cdot \pi \cdot r_c^2 \cdot h \cdot \phi \cdot c \cdot \Delta p \cdot (1 - Sw) \cdot Q_D(t_D) \tag{15}$$

where:

- Q — cumulative rate of fluid,
- r_c — inner radius of solid filter cake,
- h — thickness of bed,
- ϕ — porosity,
- c — compressibility,
- Δp — difference between bottom pressure during reconstruction and reservoir pressure,
- Sw — saturation with bound water,
- $Q_D(t_D)$— dimensionless function of rate,
- T_D — dimensionless time.

According to Hagoort (1988), the dimensionless function of rate $Q_D(t_D)$ in equation (15), should be assessed from the following dependence

$$Q_D(t_D) = \frac{2 \cdot t_D}{\ln(t_D)} \tag{16}$$

where:

t_D — dimensionless time, defined in the following equation:

$$t_D = \frac{\bar{k} \cdot t}{\phi \cdot \mu \cdot c \cdot r_c^2} \tag{17}$$

Dimensionless function of rate $Q_D(t_D)$ can also be determined using tables or plots (Slider 1983).

In reservoir engineering, damaging of the near-well zone is described by the skin effect factor (Fig. 3) described by (Slider 1983):

$$S = \left(\frac{k}{k_s} - 1 \right) \cdot \ln \frac{r_s}{r_c} \tag{18}$$

where:

k — permeability of intact zone of the rock-mass,
k_s — permeability of contaminated zone of deposit,
r_s — radius of contaminated zone, corresponding to the radius of zone occupied by filtrate r_f.

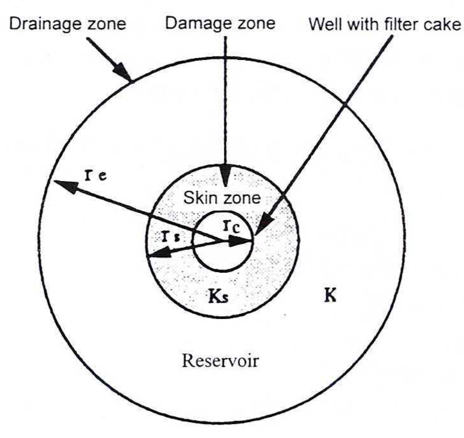

Fig. 3. Damaged zone near the well (skin effect)

Rys. 3. Strefa uszkodzona w sąsiedztwie odwiertu (skin efekt)

4. Determination of the fluid penetration zone

Fluid filtrating the deposit occupies a zone of some volume. This can be represented mathematically in the following way:

$$Q = \pi \cdot (r_f^2 - r_c^2) \cdot h \cdot \phi \cdot (1 - Sw) \tag{19}$$

where:

Q — cumulative rate of fluid.

Comparing equations (15) and (19) by sides, and employing equations (9), (16), (17), the following is obtained:

$$(r_f^2 - r_c^2) = 2 \cdot r_c^2 \cdot c \cdot \Delta p \cdot \frac{\dfrac{2 \cdot t \cdot \ln \frac{r_e}{r_c}}{\phi \cdot \mu \cdot c \cdot r_w^2 \cdot \left(\dfrac{\ln \frac{r_w}{r_c}}{k_c} + \dfrac{\ln \frac{r_f}{r_w}}{k_f} + \dfrac{\ln \frac{r_e}{r_f}}{k} \right)}}{\ln \left(\dfrac{t \cdot \ln \frac{r_e}{r_c}}{\phi \cdot \mu \cdot c \cdot r_c^2 \cdot \left(\dfrac{\ln \frac{r_w}{r_c}}{k_c} + \dfrac{\ln \frac{r_f}{r_w}}{k_f} + \dfrac{\ln \frac{r_e}{r_f}}{k} \right)} \right)} \tag{20}$$

Equation (20) has a complex form due to the radius of contaminated zone r_f, from which the radius can be calculated numerically.

5. Calculations — examples

Parameters of mud filtration were calculated, assuming the existence of three concentric zones of different permeability, and through which mud filtrates: solid filtration cake, zone of deposit occupied by mud filtrate and intact rock-mass. Calculations were made for the following input data:

- initial mean pressure — 130 bar,
- thickness of deposit — 15 m,

- permeability of intact rock-mass — 60 mD,
- permeability of contaminated zone — 20 mD,
- permeability of solid filter cake or blocker — 10 mD,
- saturation with bound water — 25%,
- porosity — 12%,
- radius of well — 15 cm,

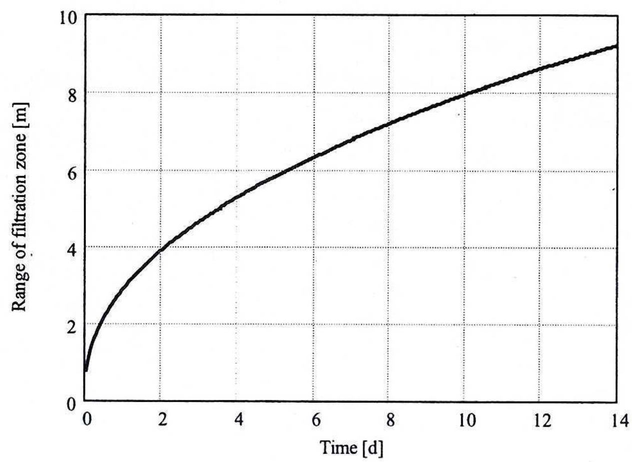

Fig. 4. Range of filtration zone

Rys. 4. Zasięg strefy filtracji

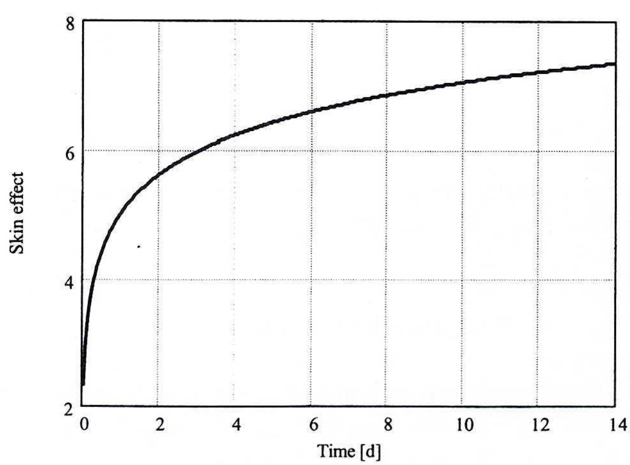

Fig. 5. Skin effect

Rys. 5. Skin efekt

- cake thickness — 3 cm
- radius of well impact — 350 m,
- compressibility of fluid — $5e^{-10}$ 1/Pa,
- viscosity of fluid — 1.1 cP,
- repression — 13 bar.

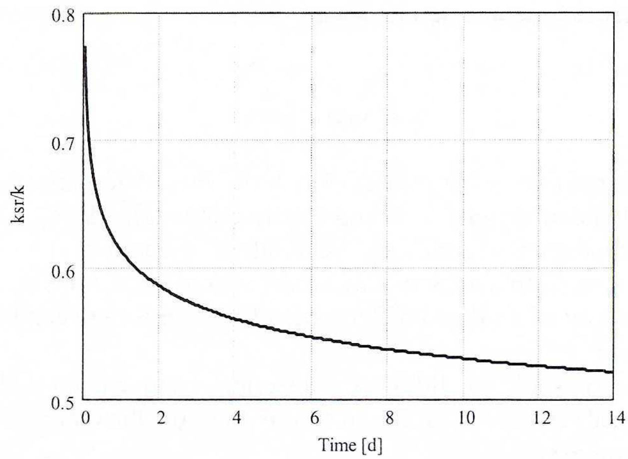

Fig. 6. Extent of variability of mean permeability

Rys. 6. Stopień zmiany przepuszczalnośc średniej

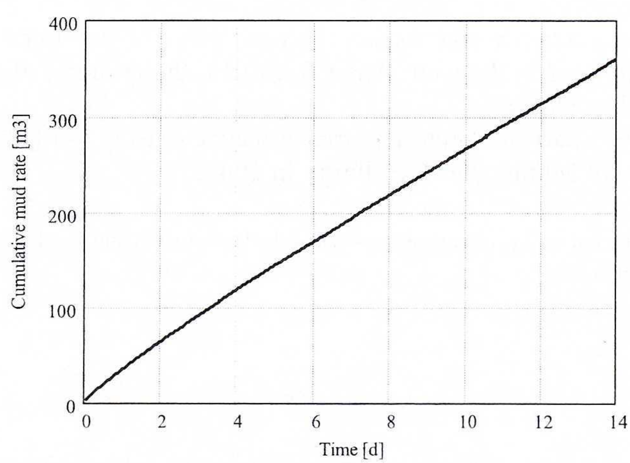

Fig. 7. Cumulative mud rate

Rys. 7. Wydatek kumulacyjny płuczki

Based on the calculation, the function of reconstruction time was assessed, range of fluid filtration, skin effect, variability of mean permeability, cumulative quantity of injected fluid in particular.

Results of calculations are presented in Fig. 4, 5, 6 and 7.

It follows from the analysis of plots in Fig. 4 to 7 that the most disadvantageous influence of mud is observed during the first stage of reconstruction. To limit the unfavourable influence of mud's filtration in the rock-mass, the use of blockers should be considered. They make a weakly permeable layer on the well's wall, which can be easily removed after the reconstruction works.

6. Conclusions

1. Reconstruction works often create the risk of permanent damaging of the near--well zone by a filtrate of drilling mud and hardly removable clayey particles.

2. The rate of deposition of solids and penetration of liquid to the deposit depends, among others, on such factors as: structure of the porous medium, size and content of solids in mud, viscosity of mud and differences of pressures between bottom pressure and reservoir pressure.

3. Fluid filtration in static conditions was described by an equation of fluid influx to well with the assumed pressure drop. Based on this solution, the range of zone subjected to fluid filtration was assessed.

4. It follows from the calculations that the most disadvantageous influence of mud is observed during the first stage of reconstruction. To limit the unfavourable influence of mud's filtration in the rock-mass, the use of blockers should be considered. They make a weakly permeable layer on the well's wall, which can be easily removed after the reconstruction works.

5. During reconstruction works, excess reservoir pressure should be minimized by the column of fluid used in the well. Apart from this, the duration of reconstruction operations should be reduced.

Paper written as a part of statute researches realized at the Drilling, Oil and Gas Faculty, University of Mining and Metallurgy in 2002.

Paper written as a part of statute researches realized at the Drilling, Oil and Gas Faculty, University of Mining and Metallurgy in 2002

REFERENCES

Civan F., 1999: Predictive models for filter cake buildup and filtrate invasion with non-darcy effects'. SPE 52149.

Dubiel S., Chrząszcz W., Rzyczniak M., 2001: Problemy dowiercania warstw perspektywicznych w otworach naftowych. Uczelniane Wyd. Nauk.-Dyd. AGH, Kraków (in Polish).

Hagoort J., 1988: Fundamentals of gas reservoir engineering. Elsevier, Amsterdam.

Herman Z., Uliasz M., 2002: Doświadczenia z zakresu ochrony pierwotnych właściwości skał zbiornikowych Przedgórza Karpat. XIII Międzynarodowa Konferencja Naukowo-Techniczna: Nowe metody i technologie w geologii naftowej, wiertnictwie, eksploatacji otworowej i gazownictwie, Kraków (in Polish).

Liu X., Civan F., 1995: Formation damage by fines migration including effects of filter cake, pore compressibility, and non-darcy flow — a modeling approach to scaling from core to field. SPE 28980.

Slider H.C., 1983: Worldwide practical petroleum reservoir engineering methods. PennWell, Tulsa.

REVIEW BY: PROF. DR HAB. INŻ. JAKUB SIEMEK, KRAKÓW

Received: 18 October 2002