Effect of wave action on near-well zone cleaning

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Abstract. Drilling filtrate invasion into the producing formation and native water accumulating of the near-well zone in well operation reduce the well productivity. As a result of that, depending on characteristic capillary pressure scale and differential pressure drawdown, oil production rate may become lower than expected one. In this paper, it is considered the hysteresis effects of capillary pressure after reversion of displacement. As applied to laboratory experiment conditions, the solution of problem of oil flow in formation model with a pressure drop on the model sides harmonically varied with time is presented. It was estimated a range of fluid vibration effective action on the near-well zone cleaning from capillary locking water. The plant simulating extraction of oil from formation using widely practised sucker-rod pump has been created. Formation model is presented as a slot filled with broken glass between two plates. In the process, natural oil and sodium chloride solution were used as working fluids. The experiments qualitatively confirm a positive effect of jack pumps on the near-well zone cleaning.

1. Introduction. Flow rate of producing well
Wells drill with use of a water clay solution, with consequent water filtrate invasion into the producing formation. Thereby, an oil or gas saturation of near-well zone reduces. When influx is made with a well bore pressure \( p = p_i \) being less than initial strata pressure \( p = p_0 \), the penetrated water filtrate is not fully displaced. Part of water remains in porous medium in an immiscible capillary-locking state. In some cases, a stratal flow characteristic change near borehole is said to be skin effect [1].

Let us consider axisymmetric steady oil influx to well in a stratum with initial oil saturation \( s = s_0 \). Suppose that the stratum is hydrophilic, so some water is capillary locked in the near-well zone. We denote \( r = R \) as coordinate of external boundary where \( s = s_0 \) and \( p = p_0 \). Let such boundary exist.

So the Muscat-Leverett system of equations for steady flow takes the form:

\[
\begin{align*}
    v &= -\frac{k}{\mu} f(s) \frac{\partial p}{\partial r}, \\
    v_i &= -\frac{k}{\mu_i} f_i(s) \frac{\partial p_i}{\partial r}, \\
    \frac{1}{r} \frac{\partial}{\partial r} (v \cdot r) &= 0, \\
    \frac{1}{r} \frac{\partial}{\partial r} (v_i \cdot r) &= 0,
\end{align*}
\]

\( p = p_i + p_c \phi(s) \).

Here \( p_c \) is the capillary pressure, the functions \( \phi(s), f_i, \) and \( f_i \) are specified on interval (0,1) and should be defined experimentally. But it should be pointed out that until now the problem of one-valued definition of these functions at the ends of mentioned above interval has not been solved. On the borehole, where \( r = r_i \), the phase pressures \( p = p_i \) are the same and are equal to \( p_c \), therefore...
At steady regime of capillary locking the relation \( p_0 - p_r = p_0^0 \phi(s_0) \) is satisfied. In this case, \( v_i = 0, \ p_i = p_c \), and for oil flow velocity we have the formula

\[
v = -\frac{k}{\mu} f(s) p_0^0 \phi'(s) \frac{\partial s}{\partial r}.
\]

Substituting this into the continuity equation for oil phase, we obtain the well production expression

\[
q = \frac{k}{\mu} f(s) p_0^0 \phi'(s) \frac{\partial s}{\partial r} = \text{const}.
\]

By integration over \( r \) between the limits \([r_c, R]\) and over \( s \) from 0 to \( s_0 \) this formula rearranges in the form

\[
q = I(s_0) \frac{k}{\mu} \frac{p_0}{\ln(R/r_c)}.
\]

Here, \( I(s_0) = \int_0^{s_0} f(s) d\phi(s) \) and, if we take the approximation \( f(s) \approx s^{3.5}, \ \phi(s) = \left[ s / (1 - s) \right]^{1/2} \), this integral can be expressed in terms of elementary functions:

\[
I(s) = \int_0^s f(s) \phi(s) ds = \frac{1}{2} \left[ s^2 (1 - s)^{3/2} \right] ds = 2 \left[ 16 - 8s - 2s^2 - s^3 \right] / \left[ \sqrt{1 - s} \right].
\]

If the capillary forces are negligible small (in this case water is also movable), so flow of fluids is homogeneous, \( s \equiv s_0 \), and for the oil influx \( q_0 \) we obtain the expression

\[
q_0 = \frac{k}{\mu} f(s_0) p_0 p_c - p_r = \frac{k}{\mu} f(s_0) p_0^0 \phi(s_0) / \ln(R/r_c).
\]

As can be seen, due to partial plugging of the near-well zone by water, the well production decreases in \( \eta \) times, where

\[
\eta(s_0) = \frac{q}{q_0} = \frac{I(s_0)}{f(s_0) \phi(s_0)}.
\]

This formula is valid for all reasonable initial values of oil strata saturation \( s_0 \) except vicinities of nil and unit where, as noted above, an approximation of experimental data of function \( \phi \) is not precise. Determined by the formula (1) the plot of function is presented on Figure 1.
2. Mixed wettable media. Reversion of displacement

Appearing in the formula for capillary pressure jump on phase boundary, parameter $p^0_k$ defines a degree of the rock wettability with water. Positive values of the parameter are typical for hydrophilic medium and negative ones are associated with hydrophobic rock. Most of oil-bearing rocks are mixed wettable. In such strata, pressures in different phases become equal in some inner points $s_e \in (0;1)$. A sign of parameter $p^0_k$ can change while immiscible displacement changes direction. As an illustration, in Figure 2 is presented the photo of oil inclusions in the water-filled quartz capillary (radius $r_i = 0.3 \times 10^{-3}$ m) [2]. Experiments show that a convexity of meniscuses changes after a change of flow velocity direction. Capillary forces impede the displacement process because the energy of particle separation from capillary surface is in excess of the energy released in the course of its adhesion to the same surface.

Under change of displacement regime or its direction in the formations saturated with oil and water, a capillary pressure is subjected to the hysteresis phenomenon. A way of plotting of hysteresis loops of capillary pressure is described in paper [3].

3. Pressure wave propagation against the background of steady-state flow

Applying to laboratory experiment conditions, we consider one-dimensional oil flow in finite-size pattern with specified pressure drop $\Delta p = p_0 - p_i$ on the sides and harmonically varied with time $p(t) = \cos \omega t$. The process is described by problem:

$$\frac{\partial p}{\partial t} = a^2 \frac{\partial^2 p}{\partial x^2}; \quad p(0,t) = p_0 + A \cos \omega t; \quad p(l,t) = p_0.$$

Here $a^2 = k / (\beta \mu)$ is pressure conductivity factor, $k$, $\mu$, $\beta$, $\omega$, and $l$ are permeability, viscosity, storage coefficient, vibration circular frequency of vibrations, pattern length respectively. Solution of problem (2) could be presented as sum of two functions $p(x,t) = p_1(x) + p_2(x,t)$, where $p_1 = p_0 + \Delta p x / l$ is a pressure distribution in steady flux, and $p_2(t) = X(x) \exp \{ -i \omega t \}$ is a periodic solution of pressure conductivity problem without initial data, satisfying boundary conditions $p_2(0,t) = A \cos \omega t; \quad p_2(l,t) = 0$.

Solution of latest problem is sought in the form $p_2 = X(x) \exp \{ -i \omega t \}$. Function $X(x)$ satisfies to the conditions:

Figure 2. Oil meniscuses after a reversion of displacement.
\[ X^* + \gamma^2 X = 0; \quad (\gamma = \gamma_0 (1 + i); \quad \gamma_0 = \sqrt{\frac{\omega}{2\alpha}}); \quad X(0) = A; \quad X(l) = 0 \] and looks like

\[ X(x) = A(X_1 + iX_2) = A \frac{\sin(\gamma(l-x))}{\sin \gamma l}. \] Separating the real parts, we find

\[ p_1(x,t) = A(X_1(x) \cos \omega t + X_2(x) \sin \omega t), \]

where

\[ X_1 = -2 \frac{\cos \gamma_0 x \sin \gamma_0 l \sin \gamma_0 (l-x) \sin \gamma_0 (l-x) \cos \gamma_0 (l-x)}{\cos 2\gamma_0 l - c \cos 2\gamma_0 l}, \]

\[ X_2 = -2 \frac{\cos \gamma_0 x \sin \gamma_0 l \cos \gamma_0 (l-x) \sin \gamma_0 (l-x) \cos \gamma_0 (l-x) \cos \gamma_0 (l-x)}{\cos 2\gamma_0 l - c \cos 2\gamma_0 l} \]

In the case of semibounded formation, one can analogously obtain the next solution:

\[ p = p_1 + p_2; \quad p_1 = p_2 + \Delta p \cdot \text{erf} \left( \frac{x}{2\alpha \sqrt{t}} \right); \quad p_2 = A \exp(-\gamma_0 x) \cos(\omega t - \gamma_0 x). \]

\[ x = 0: \quad p = p_c + A \cos \omega t; \quad x \to \infty: \quad p \to p_0. \]

Derivative of function \( p(x,t) \) with respect to \( x \) is proportional to flow velocity

\[ \frac{\partial p}{\partial x} = \left[ \frac{\Delta p}{\alpha} \right] \frac{x}{\sqrt{\pi t}} \left( \frac{a}{\sqrt{\pi t}} \right) + A \exp(-\gamma_0^2 \alpha \omega) \sin(\omega t - \gamma_0^2 \alpha x). \]

(3)

Figure 3 gives the derivatives of fluid pressure as a functions of time at the distances 0, 0.25, 0.5, 0.75, 1.0, and 3 m from output of finite stratum (stratum length \( l = 100 \) m). Other parameters are \( \gamma_0 = 1.67 \) l/m, \( \omega = 20 \) 1/min, \( A = 3 \) m, \( \Delta p = 5 \) m.

Figure 3. Subsidence of vibrational amplitude of fluid pressure with distance increasing from output.

Low curve on Figure 4 presents a theoretical distribution of oil saturation near borehole (end effect of capillary locking of water phase). Upper curve shows schematically a redistribution of both saturations at the vibration half-period after change of a flow direction. Meanwhile a part of pores is released from capillary-locking water and so the valuable product obtains access to borehole. “Swinging” helps to transform the near-well zone into neutrally-wettable one, impeding a development of capillary-locking effect.
4. Experiments
Laboratory experiments were performed on the flat model of stratum. Broken glass was taken as working porous material and filled the slot between two glass rectangle plates. Dimension of model is 0.4×0.2 m. Size of glass particles was in the range of (2 – 2.5)×10^{-4} m, slot depth was \( h = 2 \times 10^{-3} \) m. Porous volume of workspace occupied 43 % of total physical volume. Permeability of the pattern was 54 darcy. The model was saturated with oil through displacement of water up to obtaining the steady-state flow regime with the residual capillary-locking water formation in the neighborhood of outflow cross-section.

On output, the harmonic vibration of pressure were performed at specified parameters \( \omega = 2.5 \) 1/sec, \( A = 0.075 \) m, \( \Delta p = 0.1 \) m, and vibration action time was 1 hour. Referring to Figures 5a,b, we have a state of zone with width 0.1 m near output cross-section of pattern before (shot a) and after (shot b) the vibration action on flow.

![Figure 4. Mechanism of near-well zone cleaning from capillary-locking water.](image)

![Figure 5. State of zone near output before (a) and after (b) the vibration action.](image)
5. Conclusions
As a rule, a real well production is less than expected one as defined, for example, by well-known formulas of Dupuit. Drop in well production depends on physicochemical properties of stratum and fluids contained in its porous space. Change of direction of immiscible fluid displacement can vary degree and behavior of wettability of rock porous surface. As the experiments demonstrated, the superposition of harmonic action and well liquid pressure on the output helps to clean the near-well zone from immiscible capillary-locking water. This fact proves an advantage of application of jack pumps in comparison with pumps that give the constant pressure drawdown.

References
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