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Prediction and management of fines migration for oil and gas production

P. Bedrikovetsky[1], A. Zeinijahromi[1], A. Badalyan[1]*, T. Russell[1], L. Chequer[1], S. Borazjani[1], Z. You[1,2]

[1] Australian School of Petroleum, The University of Adelaide, Adelaide, 5000, Australia
[2] School of Chemical Engineering, The University of Queensland, Brisbane QLD 4072, Australia
* E-mail: alexander.badalyan@adelaide.edu.au

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Abstract. One of the widely spread causes of reservoir formation damage is fines migration. Migration of natural reservoir fines occur during commingled production of oil or gas with low-salinity water, during high-rate production or injection, with low-salinity waterflooding and its combinations with enhanced oil recovery. At least 10% of US$100 billion annual worldwide expenditure on prevention, mitigation and removal of formation damage is attributed to fines migration.

The distinguishing features of natural reservoir fines migration are mobilization of the attached particles (for example, due to water salinity decrease and pH increase, water velocity increase), their capture by straining in the rock, permeability reduction and consequent decline in well productivity and injectivity. Detachment of fines from rock grain surfaces yields an insignificant increase in permeability, whereas particle straining in thin pore throats and consequent plugging of conducting paths causes significant permeability decline. The main sources of movable fine particles in natural reservoirs are kaolinite, chlorite and illite clays; quartz and silica particles can be mobilised in low-consolidated sandstones.

Well productivity decline due to fines migration and formation damage during oil and gas production can be reliably predicted and effectively managed using laboratory data, mathematical modelling and field cases. The mathematical model for fines migration reliably predicts laboratory-based well behaviour. This model is mapped on the polymer option of Black-Oil model, allowing using commercial simulators for field development prediction under fines migration.

Fines-migration management by production rate monitoring can prevent 3-4 times decline in well productivity index. Water blocking by deliberately induced fines migration and formation damage yields sweep increase during fines-assisted low salinity waterflooding with 8% of incremental recovery and 2-to-3,7 times reduction in produced water volumes; and significant water production decrease during pressure depletion of oil or gas fields with strong water support.

These conclusions are supported by micro-scale physics theory, mathematical modelling, laboratory experiments, field data, 3D reservoir simulation and field test.

Migration of natural reservoir fines is one of the main formation damage mechanisms during waterflooding and enhanced oil recovery (EOR) operations [1] leading to well productivity decline during oil and gas production. Drastic permeability decline during sequential injections of water with decreasing salinity is accompanied with appearance of fines at the core effluent [2]. Even if the physical reason for this phenomenon wouldn't be known, it can be used in oil and gas production: decrease of water salinity with consequent permeability decline decelerates water resulting in water production reduction and sweep enhancement.

Nowadays the permeability decline under the decreasing salinity is clearly explained. Natural reservoir fines are attached to the rock surface by the attractive electrostatic force that decreases as salinity declines. Formation damage is induced by mobilization of particles initially attached to the rock surface, their migration and straining in thin pores [2]. The attached fines coat the grain surface, so their detachment does not cause high porosity and permeability decline. Yet, straining of these particles in thin pores reduces the number of available flow paths in the porous media leading to a significant growth of the hydraulic resistivity and explains the hundred-fold permeability impairment by migrating fines.

The most common fines in subterranean reservoirs are clays (e.g. kaolinite, illite, chlorite). The platelet shape of the kaolinite particles means that while detachment of kaolinite will have a small effect on the porosity, detached particles can strain in even large pore throats [3]. Typical permeability decrease for fines migration during single-phase flow of 100…1000 times is reported elsewhere [4], while the presence of residual oil decreases this number by 10…100.

Low-salinity (LS), high pH, high flowrates and elevated temperatures of reservoir and injected fluids are the most common parameters causing mobilization of natural fines in oil and gas reservoirs and aquifers and consecutive formation damage. LS-induced formation damage due to natural fines mobilization in sandstones was presented by A. Lever, and R.A. Dawe [5], and A. Badalyan et al. [6]. Step-wise reduction in fluid salinity leads to a gradual reduction of core permeability. Significant core damage is observed during corefloods with fluid salinity near to those of fresh water. Such damage is usually accompanied with increased effluent particle concentrations. LS fluid detaches natural fines at high rate causing them to move through a porous network like an "avalanche". This process is also exacerbated by the fact that kaolinite "booklets" not only expand in their size [2], but they split into separate platelets, thus significantly increasing the number of particles available for pore-throat blocking. Less formation damage occurs when a porous media is exposed to higher fluid velocities when kaolinite "booklets" are mobilized in "intact" form.

In the present paper first we explain why fines migration yields permeability decline; then we present the theory of fines migration and its validation by laboratory experiments. Afterwards, using the field examples we show how the fines-migration productivity-impairment can be managed and mitigated, and how it can be used for improved oil-gas recovery. The main conclusion of this work is the message: the developed lab, math and field test methods made fines migration predictable and manageable in order to assist oil-gas recovery.

Theory

Drag, electrostatic, lifting and gravitational forces exert a fine particle attached to the rock surface (fig. 1). The drag and lifting forces detach the particle, while the electrostatic and gravity forces attach it. It is commonly assumed that at the moment of detachment, the particle rotates around a neighbouring particle or an asperity on the grain surface.

The attaching $\vec{F}_e$ weakens as salinity decreases, explaining why the fines are released by fresh-salinity or LS water. The detaching forces increase with rate increase; hence, fines are detached at high velocities. Therefore, the condition of mechanical equilibrium of a particle on a surface is the equality of detaching and attaching torques [7–9]:

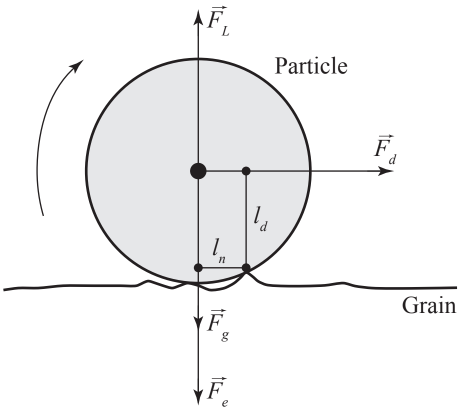

Fig. 1. **Torque balance of electrostatic ($\vec{F}_e$), gravity ($\vec{F}_g$), lift ($\vec{F}_L$) and drag ($\vec{F}_d$) forces and tangential (l_d) and normal (l_n) lever arms for attached particles**

$$F_d(U,r_s)l_d(r_s)=$$
$$=[F_e(r_s,\gamma,\mathrm{pH},T)-F_L(U,r_s)+F_g(r_s)]l_n, \qquad (1)$$

where γ is the salinity of water, further in the text called salinity; T is the temperature of a fluid/rock; r_s is the particle radius; U is the fluid velocity (Darcy's velocity).

The torque balance determines whether every single particle on the rock surface will be mobilised or not for a given velocity and salinity (in this case we consider isothermal conditions and constant pH of a fluid). Therefore, retention concentration (concentration of fine particles attached to grain surface) is a function of velocity and salinity. It is called the "maximum retention function".

If the detaching torque is weaker than the attaching torque, the particle remains on the surface, and the attached concentration is lower than the maximum. If the velocity increase or salinity decrease causes reaching the attaching torque value by the detaching torque, the fine mobilization occurs, and maximum attached concentration is reached. Therefore, the maximum retention concentration is a fundamental property of porous media and models the fines mobilization.

The higher is the velocity the lower is the maximum retention function (Fig. 2, see a). At velocity above $U_{\max}$, the electrostatic force cannot keep any single particle on the surface, and the maximum retention function is equal zero. Here, we need to stress that equality of maximum retention function to zero doesn't mean that all particles previously retained on the grain surface have been removed – only those particles have been removed which were mobilized at current fluid salinity. Point *I* corresponds to initial concentration of the attached reservoir fines. Fluid velocity increase until point *A* does not lift fines. The first fine particle is lifted at the velocity U_{cr} in point *B*. The critical velocity is an important characteristic of fines release by the rock, determining the well rate causing no fines mobilisation. The critical velocity is usually determined in routine fines-migration tests. Besides U_{cr}, the maximum retention function provides the amount $\Delta\sigma_U$ of fines, released during velocity increase up to point *C*.

Similarly, the path "*I–A–B*" corresponds to salinity decrease and release of the first particle by salinity γ_{cr} (see fig. 2b). This point corresponds to critical salinity, usually also determined in routine fines-migration tests. What the maximum retention function allows to calculate besides the γ_{cr} value is the amount $\Delta\sigma_\gamma$ of fines, released during salinity decrease.

This model assumes that the drag, lift, gravitational, and electrostatic forces describe the mechanical equilibrium for attached particles as outlined in the previous section. Here, all attached particles are assumed to have the same size and electrostatic properties. The pore space is modelled as a bundle of square, parallel capillaries with the same size.

Particles attach to the pore walls in discrete layers. As more particle layers appear, the cross-sectional area within the pore that is available for flow decreases. Thus, the flow velocity increases, increasing the drag and lifting forces with an inverse dependency on the pore size. Therefore, as more layers of particles appear, the condition for mechanical equilibrium shifts further towards detachment. At some critical internal cake thickness, h_c, any additional layers of attached particles would be unstable and detach. This cake thickness, when up-scaled, defines the maximum concentration of particles that can be attached for given values of total fluid velocity, fluid salinity, pH, etc.

Due to the assumption of spherical particles, accompanied by the assumption that the particles will arrange evenly on the pore space makes it possible to approximate the lever arm ratio $\frac{l_d}{l_n}$ as $\sqrt{3}$. Given this assumption, the torque balance can be evaluated as:

$$F_e + \frac{4\pi r_s^3}{3}\Delta\rho g - \chi r_s^3\sqrt{\frac{\rho\mu U^3}{(H-2h_c)^3}} = \frac{\sqrt{3}\omega\pi\mu r_s^2 U}{H-2h_c}, \qquad (2)$$

where where g is gravitational acceleration; H is the height of the rectangular pore channel; μ is

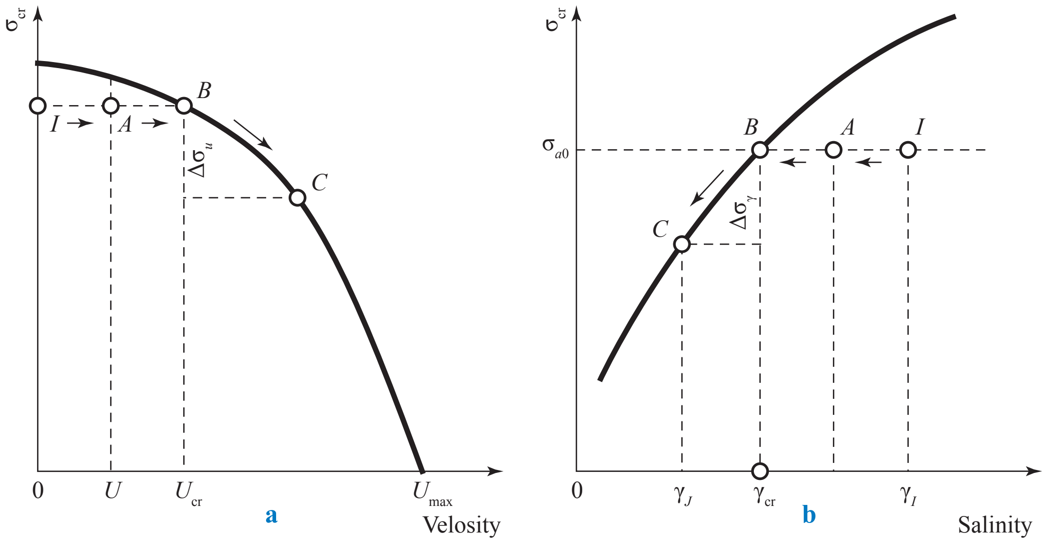

Fig. 2. **The maximum retention function: detached particle concentration, σ_{cr}, as a function of the fluid velocity (a) and the fluid salinity (b)**

dynamic viscosity of the carrier fluid; ρ is density of the carrier fluid; Δρ is the density difference between the suspended particle and the carrier fluid; χ is the correction factor for lifting force; ω is the correction factor for drag force.

For rectangular pores, the critical retention function can be related to the critical cake thickness as per:

$$\sigma_{\text{cr}} = \left[1-\left(1-\frac{h_c}{H}\right)^2\right](1-\phi_c)\phi, \tag{3}$$

where ϕ_c is the porosity of the internal filter cake formed by attached particles. This parameter is often unknown and must be determined empirically.

Removing the gravitational and lift forces from the torque balance equation (2) and substituting the resulting expression into equation (3) yields the expression for the critical retention function:

$$\sigma_{\text{cr}}(U,\gamma,\text{pH},T) = \\ = \left[1-\left(\frac{1}{2}+\frac{\sqrt{3}\omega\pi\mu r_s^2 U}{2F_e(\gamma,\text{pH},T)H}\right)^2\right](1-\phi_c)\phi. \tag{4}$$

The above equation provides the qualitative descriptions of particle detachment as outlined above. This equation predicts decrease in σ_{cr} both with increase in fluid velocity and decrease in fluid salinity, which will decrease the electrostatic force. Both of these dependencies are monotonic. Schematic graphs presenting typical forms of the critical retention function plotted against the fluid velocity and fluid salinity (see fig. 2ab) demonstrate the monotonic decline of σ_{cr} both with an increase of fluid velocity and decrease of fluid salinity. Both forms also show the highly non-linear dependency of σ_{cr} on the injection conditions.

The traditional colloidal flow model assumes simultaneous attachment and detachment of colloidal particles in porous media [10–13]:

$$\frac{\partial\sigma_a}{\partial t} = \lambda c U - k_{\text{det}}\sigma_a, \tag{5}$$

where the attachment rate is proportional to the advective flux of suspended particles cU, and the detachment rate is proportional to the attached concentration. Here t is time; c and σ_a are the suspended and attached concentrations correspondingly; λ is the filtration coefficient, which is the particle capture probability per unitary length of its trajectory; and k_{det} is the kinetic detachment coefficient, which is the reciprocal to reference detachment time.

Kinetic equation (5) is analogous to the equation for non-equilibrium adsorption, where adsorption and desorption occur simultaneously. Equilibrium sorption corresponds to equality of adsorbed and desorbed rates. The rate expression for non-equilibrium adsorption reflects interface mass transfer that is proportional to the difference between Gibbs potentials of dissolved and adsorbed matter. However, the work of dissipative drag force F_{d} that is present in the condition of mechanical equilibrium (1) cannot be included into an energy potential, resulting in velocity-dependent attached concentration.

Kinetics equation (5) does not reflect mechanical equilibrium conditions expressed by equation (1). Filtration function can be derived by averaging of micro-scale flow in a pore, while detachment coefficient is pure phenomenological and cannot be derived from microscopic physics.

On the contrary to the above-mentioned shortcomings of equation (2), the proposed modified particle detachment model follows from the torque balance condition of mechanical equilibrium (1). Consider the particle ensemble on the rock surface, and apply the flow with given U, γ, pH, T, etc. For each particle, equation (1) makes it possible to define whether the particle is attached to the rock or is lifted by the detaching torques. The particles submitted to detaching torques that exceed the attaching torque defined by the maximum electrostatic attraction, are mobilized. It makes the attached concentration of remaining fines a function of U, γ, pH, T, etc., which is called the maximum retention function [14–16]. The interface mass transfer by particles between the solid and fluid becomes

$$\frac{\partial\sigma_a}{\partial t} = \begin{cases}\lambda c U, & \sigma_a < \sigma_{\text{cr}}(U,\gamma) \\ \sigma_a = \sigma_{\text{cr}}(U,\gamma), & \sigma_a = \sigma_{\text{cr}}(U,\gamma)\end{cases}, \tag{6}$$

i.e. the particles attach until reaching the maximum retention value, and afterwards the attached concentration remains equal to the maximum retention function. Continuous particle detachment during flows with decreasing fluid salinity or increasing velocity and pH corresponds to second line of equation (6), where time variations of U, γ, pH and T result in decrease of the maximum retention function.

Experimental validation of maximum retention function

Schematic of an experimental setup used in the present study for single- and two-phase corefloods are presented elsewhere [17], respectively. Laboratory-based results for maximum retention functions during velocity-increase tests for two sandstones A_1 and A_2 fitted by the proposed modified mathematical model are presented in Fig. 3. Good fit of the model to lab data validates the modified fines-mobilisation model that is based on the notion of the maximum retention function.

Good agreement also exists between laboratory-measured [5] and predicted values of the maximum retention function during salinity-decrease tests as reported in our previous paper [18].

Fines migration management to maintain well productivity

The field data on well rate response, *Q*, to continuously increasing pressure drawdown, ΔP, (Fig. 4) were matched by a mathematical model in a detailed fines migration study of Gulf-of-Mexico reservoir [19]. For low ΔP values, where fines are not lifted the well responds with the rate increase. High drawdowns cause the fines release and further rate decline. High quality of matching suggests a reliable prediction of well behaviour during fines migration, i.e. the fines migration is predictable. If the pressure drawdown would be fixed at the medium level (28 MPa), the rate decrease and 3-4 times decline in well productivity index wouldn't occur. Therefore,

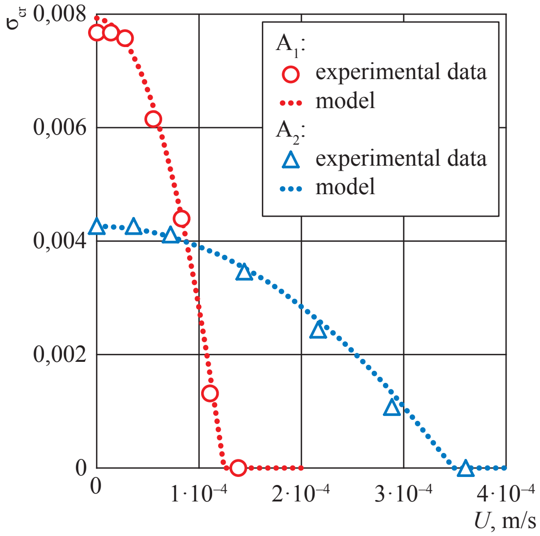

Fig. 3. **Validation of the maximum retention function by the laboratory test for two sandstone cores A_1 and A_2**

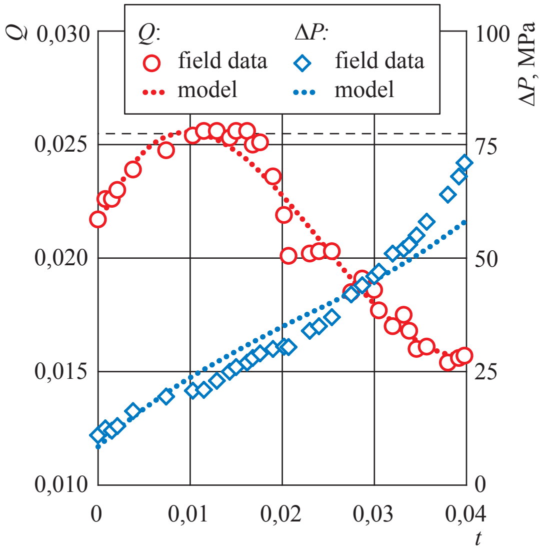

Fig. 4. **Data on well rate response to continuously increasing pressure drawdown as functions of dimensionless time *t***

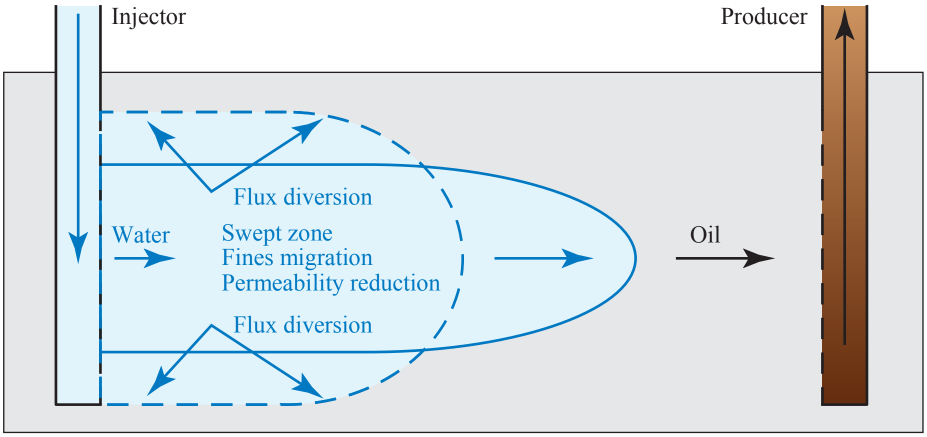

Fig. 5. **Fines-migration-assisted mobility control and produced water management**

pressure drawdown management results in the formation damage mitigation, i.e. the fines migration is manageable.

Fines-migration-assisted mobility control and produced water management

Consider waterflooding in a reservoir where permeability increases from top to the central area and decreases back to the bottom (Fig. 5). Preferential propagation of water in the central zone yields fast water breakthrough, low sweep and, consequently, the usual low recovery. Salinity reduction in the injected water causes fines mobilisation with consequent permeability decline and deceleration of the injected water. LS-water front lags behind the "normal"-water front. The excess of water is diverted into the unswept low-permeable zones. So, the induced fines migration triggers the mobility control during smart waterflooding. It makes LS waterflood the mobility-control EOR method, like polymer injection. The effect is similar to that of polymer adsorption that also yields the permeability reduction. The analogy allows mapping the flow equations for fines-assisted waterflooding onto polymer flood equations. Therefore, the polymer option of conventional Black-Oil simulators can be used for reservoir simulation for water-oil flow with fines migration.

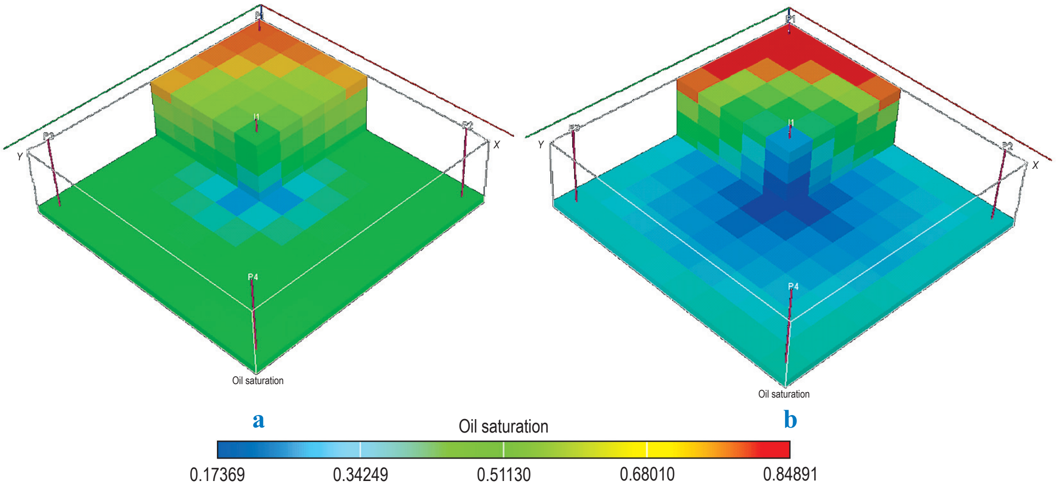

Fig. 6. **Normal (a) and LS-fines-assisted (b) waterfloodings after 0,4 pore volumes injected (PVI) – results of 3D reservoir simulation by Eclipse**

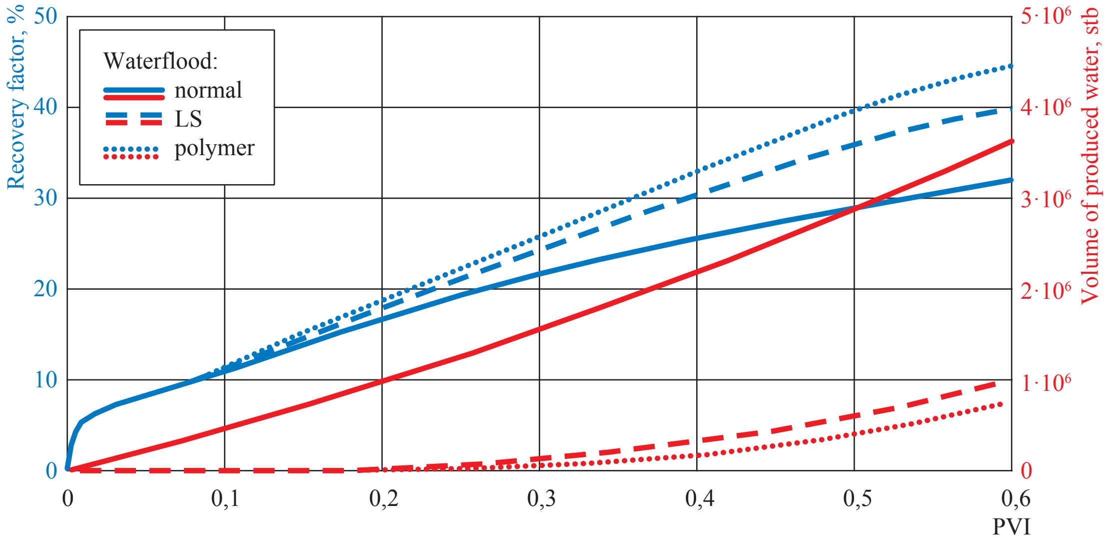

Fig. 7. **Comparison between polymer flood, normal and fines-assisted waterfloodings (Daqing field)**

3D-modelling in 5-layer-cake 5-spot pattern in Fig. 6 also shows that fresh-water injection results in breakthrough moment decrease and in significant decrease in residual oil in all layers [20, 21]. Highly permeable layer at the moment of 0,6 PVI is completely swept in the case of fresh water injection while a significant amount of residual oil remains in high permeable layer during normal waterflooding. The residual oil in swept zone is significant lower for fresh waterflood rather than for normal waterflood.

For the modelled Daquin field case, the recovery factor after 0,6 PVI increases from 32% for normal waterflood to 40% at the fines-assisted waterflood and up to 43% at programmed polymer slug injection as shown in Fig. 7 [21]. If compared with normal waterflood, application of fines-assisted flooding results in 2-to-3,7 times decrease in produced water; application of polymer flood decreases the amount of produced water 2,8-to-4,6 times. Fines-assisted flooding results in significant reduction of water cut and increase of the breakthrough time if compared with the normal waterflood; the water cut reduction and waterless production period increase with polymer flooding are higher: water cut decreases from 0,77 to 0,59 due to fines-assisted flooding being 0,55 for polymer flooding after 0,6 PVI. Yet, the induced fines migration results in increase of the pressure drop across the reservoir or in the injection rate decrease due to decrease of permeability in the swept zone.

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Analysis of laboratory and field data together with mathematical modelling of salinity fines migration allow drawing the following conclusions:

- the modified mathematical model for fines migration allows for reliable laboratory-based well behavior prediction;
- the model is mapped on the polymer option of Black-Oil model, allowing using commercial simulators for field development prediction under fines migration;
- fines-migration management by production rate monitoring can prevent 3-4 times decline in well productivity index; and
- water blocking by deliberately induced fines migration and formation damage yields sweep increase during fines-assisted LS waterflooding with 8% of incremental recovery and 2-to-3,7-times reduction in produced water volumes, and significant water production decrease during pressure depletion of oil or gas fields with strong water support.

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Прогноз и контроль миграции мелкодисперсных частиц в процессе нефте- и газодобычи

П.Г. Бедриковетский[1], А. Зейнижахроми[1], А.Г. Бадалян[1*], Т. Рассел[1], Л. Чекер[1], С. Боражани[1], Ч. Ю[1,2]

[1] Австралийская школа нефти, Университет Аделаиды, Австралия, 5000, г. Аделаида
[2] Химико-технологическая школа, Квинслендский университет, Австралия, QLD 4072, г. Брисбен
[*] E-mail: alexander.badalyan@adelaide.edu.au

Тезисы. Одной из широко распространенных причин повреждения пород-коллекторов при добыче нефти или газа является миграция пластовых мелкодисперсных частиц вследствие смешивания нефти или газа со слабоминерализированной попутной пластовой водой, высокоскоростной добычи или закачки, заводнений скважин слабоминерализированной водой и их комбинирования с интенсификацией добычи. Ежегодно как минимум 10 % общемировых расходов (100 млрд долл. США) на предотвращение, смягчение и ликвидацию отрицательных последствий повреждения коллекторов обусловлены миграцией мелкодисперсных частиц.

Характерными особенностями миграции пластовых мелкодисперсных частиц являются: мобилизация частиц, прикрепленных к поверхности зерен горной породы, из-за снижения уровня минерализации воды, повышения ее водородного показателя либо увеличения скорости потока; захват мобилизованных частиц порами горной породы; снижение проницаемости пласта и, соответственно, падение продуктивности и приемистости скважин. Отделение мелкодисперсных частиц от поверхности зерен горной породы приводит к незначительному росту ее проницаемости. Вместе с тем частицы забивают тонкие устья пор и, соответственно, проводящие каналы, и в конечном итоге результирующая проницаемость пласта сильно ухудшается. Основными источниками подвижных мелкодисперсных частиц в коллекторах служат каолиниты, хлориты и иллитовая глина; частицы кварца и кремнезема могут отделяться в слабосцементированных песчаниках.

Падение продуктивности скважин в результате миграции мелкодисперсных частиц и повреждение пород-коллекторов при добыче нефти и газа можно надежно прогнозировать и эффективно регулировать с использованием лабораторных данных, результатов промысловых измерений и математического моделирования. Так, математическая модель, разработанная на основе «полимерной» опции модели Black-Oil и учитывающая миграцию мелкодисперсных частиц, демонстрирует хорошую сходимость с лабораторными данными, что подтверждает применимость коммерческих средств моделирования для прогнозирования разработки месторождений в условиях миграции мелкодисперсных частиц коллектора.

Контроль мелкодисперсной миграции посредством мониторинга дебита скважины способен предотвратить трех-четырех-кратное снижение ее продуктивности. В случае заводнения скважины слабоминерализованной водой блокирование воды путем преднамеренно индуцированной миграции мелкодисперсных частиц приводит к 8%-ному приращению коэффициента извлечения углеводородов и в 3…3,7 раза сокращает объемы выбросов попутной пластовой воды; также можно существенно снизить объем воды, потребляемой для интенсификации притока в истощенном пласте.

Данные выводы базируются на принципах микромасштабной физической теории, а также на результатах математического моделирования, лабораторных и полевых экспериментов и трехмерного геологического моделирования.

Ключевые слова: повреждение породы-коллектора, миграция мелокодисперсных частиц, снижение продуктивности скважины, математическое моделирование.