MECHANISMS, MODELING, AND EFFECT OF PARTICULATE PROCESSES IN COMPLETION AND FORMATION DAMAGE

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Abstract

Phenomenological modeling of the various particulate processes causing completion and reservoir formation damage are reviewed. The mechanisms involved in the mobilization, migration, and deposition of fine particles are discussed and described mathematically. A number of case studies are presented, demonstrating the effect of particulate processes on completion damage, well impairment, and reservoir formation damage.

Introduction

Fine particle mobilization, migration, and deposition problems occurring in the reservoir formation and well completion may reduce the performance of the oil and gas production from petroleum reservoirs. Understanding the mechanisms by which fine particles cause additional pressure drop and skin effect may help develop optimal strategies for reducing and controlling their adverse effects in the field.

The processes governing the fine particle behavior during the flow of oil, gas, and brine through the reservoir formation and well completion system are very complicated in nature and affected by various factors. The rate of these processes strongly depends on temperature, pressure, and other relevant factors. Consequently, the adverse affects may be controlled by controlling such conditions. However, this requires a scientific and practical understanding of these processes.

From the practical point of view, the primary objective is obtaining simplified mathematical models for the complicated particle transport processes and their interactions with the reservoir formation. The important processes involved in fines migration and deposition in completion and porous media are:

- Deposition and detachment of fine particles at pore surfaces
- Fines migration, aggregation, and interface transfer in multi-phase fluid systems
- Effect of mechanical, chemical and thermal processes on particle behavior
- Effect of salinity and temperature shocks on particle behavior
- Alteration of pore connectivity, preferential hydraulic paths, and permeability of porous media by particulate processes
- Phenomenological modeling of particulate processes in single- and multiple-porosity media
- Porous media formulation, averaging, and simulation of particulate transport equations.

In this paper, a review of the phenomenological modeling of the various particulate processes causing completion and reservoir formation damage are provided. The mechanisms involved in the migration, deposition, and mobilization of the fine particles are described mathematically. The various problems created by fine particles at the pore surface, clogging and dislodgment of the pore throats, aggregation, and interface particle transfer processes in multi-phase fluid systems flowing through porous media are described. The implications of the various mechanical, chemical, and thermal processes on the behavior of the particles are discussed. The salinity and temperature shocks phenomena and their effects on the particulate processes are explained. The alteration of the pore connectivity, preferential hydraulic paths, permeability and porosity of porous media as a result of the various particulate processes are formulated. The phenomenological modeling of the particulate processes in single- and multiple-porosity reservoir formations is presented. The applications may involve the completion damage by particles, injectivity decline in water flooding wells, formation damage by drilling mud invasion, formation damage in naturally fractured reservoirs, asphaltene deposition, and sand production and gravel pack damage. The damage of the common completion techniques by particulate processes is illustrated by various examples. A number of case studies are presented, demonstrating the effect of particulate processes on completion damage, well impairment, and reservoir formation damage. Topics of practical importance and areas needing further research are delineated.

Porous Media Realization

The nature of particulate processes and their damage on reservoir formation depends on the mutual affects between fine particles, reservoir fluids, and porous rock formation. Properties of porous media undergoing various types of particulate processes vary and in turn affect the particulate processes (Civan, 2000). Therefore, a dynamic description of porous media is required.

The frequently resorted approaches used for porous media realization are classified into two groups: a) network models and b) bundle-of-leaky-capillary-tubes models. The network models serve as important research tools for detailed scientific investigation of the local pore level particulate behavior in porous media. Topographic images of actual pore space or prescribed synthetic pore structures can be used to simulate the consequences of the particulate processes in porous media. However, description of particulate phenomena on network models is computationally very demanding and is not practical for applications at reservoir scale simulation. This problem can be alleviated conveniently using the bundle-of-leaky-capillary-tubes models (Civan, 2001, 2002).

The leaky tube model is an extension of the bundle of capillary tubes model of porous media which led to the development of the popular Kozeny-Carman equation of permeability. In the Kozeny-Carman model, there is no interaction between the hydraulic flow paths represented by the bundle of tubes. The leaky-tube model developed by Civan (2001, 2002) allows cross-flow between the bundle of tubes, the magnitude of which is controlled by the coordination number and the valve effect of the pore throats. Because the power-law permeability equation resulting from the leaky-tube model is a simple model, it does not introduce additional computational burden on the available reservoir simulators and therefore advantageous over the network models.

There are several important factors affecting particle transport in porous media. These are discussed in the following. The hydraulic tube diameter is given by the fractal equation (Civan, 2001)

$$D_h = \lambda A_h^{\delta} \tag{1}$$

For circular tubes

$$\lambda = 2/\sqrt{\pi}, \delta = 1/2 \tag{2}$$

Tortuosity of preferential hydraulic paths is defined by:

$$\tau = L_f / L \tag{3}$$

Tortuosity affects the interstitial fluid velocity, given by (Dupuit, 1863):

$$v_f = \tau u_f / \phi \tag{4}$$

Particles attached to tortuous flow paths may be swept from the pore surface with less shear-stress because fluids move faster in tortuous paths (Civan, 2006). Coordination number represents the number of pore openings to neighboring pores. Coordination number is an integer for a given pore space. However, when averaged over the representative elemental volume of porous rock, it may assume a non-integer value (Civan, 2001, 2002). Coordination number determines the pore connectivity and cross flow between the preferential flow paths. Particle deposition, and grain cementation, fusing, and embedment may cause porosity reduction and loss of pore connectivity. The specific pore surface available in porous media is a critical parameter in determining the interaction between particles and porous media. The effective hydraulic tube surface vs. total pore surface is related by a fractal equation as:

$$\Sigma_p = C\left(V_b \Sigma_b\right)^{D/3} \tag{5}$$

The pore surface per bulk volume vs. pore surface per grain volume is related by:

$$\Sigma_b = \Sigma_g \left(\alpha - \phi\right) \tag{6}$$

Where the cement exclusion factor, given by

$$a = 1 - a_c \tag{7}$$

Where a_c is the volume fraction of the cementation and grain consolidation in bulk porous media. The fractional area open for flow, frequently referred to as areosity, determines the cross-sectional area of porous rock allowing flow through. It can be expressed conveniently using a fractal equation as:

$$A_f / A_b = c\phi^{d/3} \tag{8}$$

Where c = 1.0 and d = 3 for a non-fractal object.

Particulate Processes in Porous Media

Commonly encountered particulate processes in porous media can be classified into three categories: a) Pore surface processes, b) pore-throat processes, and c) pore volume processes (Civan, 2000). Particulate phenomena in pores are affected by various forces. The forces for particle attachment include the London-van der Waals and friction-drag and hydrodynamic thinning. The forces for particle detachment are shearing, electrostatic double-layer, and born repulsion types. The forces for particle migration (relative motion) are of the inertia, gravity (buoyancy), centrifugal, diffusion, and hydrodynamic types.

Particle behavior under the effect of these forces strongly depends on the salinity, temperature, and flow rate variations. Salinity Shock results when the injected brine salinity is lower than the critical salt concentration (CSC) (Khilar and Fogler, 1983). This causes the release or expulsion of the particles loosely attached to the pore surface into the flowing stream with the potential of pore throat plugging and causing formation damage. Salinity variation may also cause particle and formation swelling problems. When enlarged by swelling, particles are more susceptible to mobilization by the fluid shear-stress.

The temperature effect on the various parameters involving the particulate processes may be expressed either by the Arrhenius equation (wettability index) and the Vogel-Tammann-Fulcher equation (particle-particle pull-off adherence) (Civan, 2001, 2002, 2006). Temperature shock results when the temperature variation causes a change of conditions favorable from attachment to detachment of particles (Gupta and Civan, 1994).

There exists a critical mobilization velocity (Gruesbeck and Collins, 1982) above which particles loosely attached to the pore surface can be detached from the surface by the fluid shear. It corresponds to the case when the fluid shear-stress is equal to the critical shear-stress required for particle mobilization. The critical shear-stress and fluid shear-stress are defined respectively, by Potanin and Uriev (1991) as

$$\tau_{cr} = H/\left(24dl^2\right) \tag{9}$$

and Metzner and Reed (1955) as

$$\tau = k'\left(4v/r_c\right)^{n'} \tag{10}$$

The detachment rate coefficient can be estimated by (Bell, 1978, Pierres et al., 2002, Civan, 2006):

$$k_o = k_\infty \exp\left[\frac{xF}{k_B T}\right] \tag{11}$$

F : distractive force causing detachment
X : interaction length,
k_B : Boltzmann constant
T : the absolute temperature
K_∞ : pre-exponential coefficient

Determination of the critical fines mobilization interstitial velocity is based on the Forchheimer equation (Amaefule et al., 1987):

$$\frac{\Delta p}{v} = \frac{\phi \mu L}{K} + \left(\phi^2 \rho \beta L\right) v \tag{12}$$

Effect of pH is important on the critical fines mobilization interstitial velocity (Amaefule et al., 1987).

Kinetics of Particulate Rate Processes

Particulate rate processes can be described by kinetic equations. Pore surface deposition rate is given by:

$$\frac{d\varepsilon_d}{dt} = k_d\left(\alpha + u\right)\cdot \sigma_p \phi^{2/3} \tag{13}$$

$$\varepsilon_d = \varepsilon_{d_o}, t = 0 \tag{14}$$

Rate of colloidal release of particles at pore surface is given by:

$$\frac{\partial \varepsilon_r}{\partial t} = -\left(1+\alpha\right) k_r \varepsilon_p \eta_e \phi^{2/3}\left(c_{cr} - c\right) \tag{15}$$

$$\varepsilon_r = \varepsilon_{r_o}, t = 0 \tag{16}$$

α = volumetric expansion coefficient
C_{cr} = critical salt concentration (crystalline to osmotic swelling transition condition)
η_e = fraction of unblocked particles
$k_r \neq 0$, when $c < c_{cr}$
$k_r = 0$, otherwise.

Rate of hydraulic mobilization (erosion) of particles at pore surface is given by:

$$\frac{\partial \varepsilon_e}{\partial t} = -\left(1+\alpha\right) k_e \varepsilon_p \eta_e \phi^{2/3}\left(\tau - \tau_{cr}\right)$$
$$\varepsilon_e = \varepsilon_{e_o},\ t = 0 \tag{17}$$

τ_{cr} = critical shear stress
τ_w = wall shear stress
$k_e \neq 0$, when $\tau_w > \tau_{cr}$
$k_e = 0$, otherwise.

Rate of pore throat plugging deposition is given by:

$$\frac{\partial \varepsilon_t}{\partial t} = k_t u \sigma_p \phi$$
$$\varepsilon_t = \varepsilon_{t_o}, t = 0 \tag{18}$$

Where $k_t \neq 0$ when $\beta < \beta_{cr}$ (bridging) and $k_t = 0$ otherwise (non-bridging). These depend on the pore throat blocking conditions, which cause the valve effect of pore throats (Chang and Civan, 1997, and Ochi and Vernoux, 1998). Pore throat plugging criterion is described by:

$$\beta_{cr} = A\left(1 - e^{-B\mathrm{Re}_p}\right) + C \tag{19}$$

Where the pore throat to particle diameter ratio and the particle Reynolds number are defined, respectively, as:

$$\beta = \frac{D_t}{D_p} \tag{20}$$

$$\mathrm{Re}_p = \frac{c_p u D_p}{\mu \phi} \tag{21}$$

However, a flow reversal may cause particle dislodgement and redeposition at opposite pore throats. Frequent pore throat plugging and unplugging can cause a pH change in the brine because of longer exposure times between brine and pore minerals when the brine is trapped behind the blocked pore throats (Arcia and Civan, 1992).

Fines migration, aggregation, and interface transfer in multi-phase fluid systems are important problems. Particles in multi-phase fluid systems interact in complicated ways. Transfer of a wetting particle from nonwetting to wetting phase can be described as following (Civan, 2000):

Nonwetting Phase - Interface - Wetting Phase (22)
(1) (1-2) (2)

$$\frac{dR_1}{d\left(t-t_1\right)} = -\lambda_1 R_1 \tag{23}$$

$$\frac{dR_{12}}{d\left(t-t_{12}\right)} = \lambda_1 R_1 - \lambda_2 R_{12} \tag{24}$$

$$\frac{dR_2}{d\left(t-t_2\right)} = -\lambda_2 R_{12} \tag{25}$$

$$R_1 = R_1^o, R_{12} = R_{12}^o, R_2 = R_2^o, t = 0 \tag{26}$$

Particles multiply their size by aggregation. Particle aggregation kinetics may be diffusion-limited or reaction-limited.

Alteration of Porous Media

Deposition of particles in porous media causes permeability impairment. Permeability variations can be determined as a result of porosity variation by particle deposition. Effect of particle packing efficiency on porosity is described by an empirical equation as:

$$\phi = \phi_o - \alpha \varepsilon^n \tag{27}$$

Where α and n are empirical parameters.

The equation of permeability can be satisfactorily described by the Power-law (Civan, 2001-2005)

$$\sqrt{\frac{K}{\phi}} = \Gamma\left(\frac{\phi}{\alpha-\phi}\right)^{\beta} \tag{28}$$

Parametric relationships are given by:

$$\frac{\left(\beta^{-1}\right)_{max} - \beta^{-1}}{\left(\beta^{-1}\right)_{max} - \left(\beta^{-1}\right)_{min}} = \left[\frac{\Gamma_{max} - \Gamma}{\Gamma_{max} - \Gamma_{min}}\right]^{C/A} = \left[\frac{\phi^u{}_{min} - \phi^u}{\phi^u{}_{min} - \phi^u{}_{max}}\right]^{C/A} ; \; u < 0 \tag{29}$$

Porous media averaging

The equations describing the particulate processes cannot be solved without the equations describing the multi-phase fluid behavior in porous media. In general, such equations are derived by averaging over the representative elementary volume of porous media. For this purpose, two different definitions of averaging are available, as described below:

Volume average (Slattery, 1972)

$$\langle f \rangle = \frac{1}{V}\int_V f dV \tag{30}$$

Mass-weighted volume average (Gray et al., 1993)

$$\bar{f} = \frac{\frac{1}{V}\int_V \rho f dV}{\frac{1}{V}\int_V \rho dV} = \frac{\langle \rho f \rangle}{\langle \rho \rangle} \tag{31}$$

Frequently, the mixed use of the volume and mass-weighted volume averages in describing transport in porous media yields confusing results. For example, the equation of continuity is usually given in the following conventional form (Gray et al., 1993):

$$\frac{\partial}{\partial t}\left(\varepsilon_j \rho_j\right) + \nabla \cdot \left(\rho_j \varepsilon_j \bar{v}_j\right) = q_j \tag{32}$$

$\bar{v}_j$: Mass-weighted volume average

In practical applications, the users do not ordinarily distinguish between the volume and mass-weighted volume averages. The consistent form of Eq.(32), where all the variables are expressed only in volume averaged quantities is given by (Civan, 2002):

$$\frac{\partial}{\partial t}\left(\varepsilon_j \rho_j\right) + \nabla \cdot \left(\rho_j \varepsilon_j v_j\right) = \nabla \cdot \left[D_j \cdot \nabla\left(\varepsilon_j \rho_j\right)\right] + q_j \tag{33}$$

v_j : Volume average

The first term appearing on the right of Eq.(33) can be referred to as transport by the hydraulic dispersion effect, which has been generally omitted in petroleum engineering applications.

Previous studies mostly considered a single-porosity and single-permeability modeling approach. However, when reservoir formation is highly heterogeneous, a multi-porosity and multi-permeability media treatment is necessary (Bai et al., 1995). Consequently, the model becomes complicated. This difficulty can be circumvented by resorting to a plugging-nonplugging paths approach according to Gruesbeck and Collins (1982). Applying this approach, Civan and Nguyen (2005) successfully developed a simulator for fines migration and deposition in porous media.

The governing balance equations are written on the stationary and flowing (mobile) phases. Stationary phases consist of a) Porous matrix and b) Immobile fluids and deposits. Flowing phases consist of a) Gas, b) Oil, c) Water, and d) Particles and precipitates. The J-phase mass balance is given by:

$$\frac{\partial}{\partial t}\left(\varepsilon_j \rho_j\right) + \nabla \cdot \left(\rho_j u_j\right) = \nabla \cdot \left(\varepsilon_j D_j \cdot \nabla \rho_j\right) + \varepsilon_j \dot{m}_j \tag{34}$$

The J- phase momentum balance (Forchheimer equation) is given by

$$u_j = -v_j^{-1} k_{rj} \cdot N_{ndj} \cdot K \cdot \nabla \psi_j$$
$$v_j = \frac{\mu_j}{\rho_j}$$
$$N_{ndj} = \left[I + \mathrm{Re}_j \right]^{-1} \qquad (35)$$
$$\mathrm{Re}_j = v_j^{-1} \left| u_j \right| \cdot K \cdot \beta$$

The flow potential and inertial flow coefficient are given, respectively, by (Liu et al., 1998):

$$\psi = \int_{P_o}^{P} \frac{dp}{\rho} + g\left(z - z_o\right)$$
$$\beta = \frac{8.91x10^8 \tau}{\phi K} \qquad (36)$$

Particle properties play an important role in formation damage. The particle i mass balance in j-phase is given by:

$$\frac{\partial}{\partial t}\left(\varepsilon_j \rho_j w_{ij}\right) + \nabla \cdot \left(\rho_j w_{ij} u_j\right) = \nabla \cdot \left(\varepsilon_j \rho_j D_{ij} \cdot \nabla w_{ij}\right) + \varepsilon_j \dot{m}_{ij} \qquad (37)$$

Applications

Three cases are considered: a) compressible cake filtration, b) deep-bed filtration, and c) near-wellbore scale deposition.

Case I- Compressible Cake Filtration (Civan, 1998)

Particles in slurry are classified into two groups:

- Particles larger than the pores of porous media form the filter cake
- Particles smaller than the pores, migrate into and deposit in the cake and porous media

The cake-thickness-averaged material balance equations are given by:

$$\frac{d}{dt}\left[\left(r_w^2 - r_c^2\right)\overline{\in}_s\right] = 2r_c N_{ps}^{\sigma} + \left(r_w^2 - r_c^2\right)\overline{N}_{p2s} \qquad (38)$$

$$\frac{d}{dt}\left[\left(r_w^2 - r_c^2\right)\overline{\in}_{p2s}\right] = 2r_c N_{p2s}^{\sigma} + \left(r_w^2 - r_c^2\right)\overline{N}_{p2s} \qquad (39)$$

$$\frac{d}{dt}\left[\left(r_w^2 - r_c^2\right)\overline{\in}_l\right] + \left(\in_l\right)_{slurry}\frac{dr_c^2}{dt} = 2r_c\left(u_l\right)_{slurry} - 2r_w\left(u_l\right)_{filter} \qquad (40)$$

$$\frac{d}{dt}\left[\left(r_w^2 - r_c^2\right)\overline{\in}_{p2l}\right] + \left(\in_{p2l}\right)_{slurry}\frac{dr_c^2}{dt} = 2r_c\left(u_{p2l}\right)_{slurry} - 2r_w\left(u_{p2l}\right)_{filter} - 2r_c N_{p2s}^{\sigma} - \left(r_w^2 - r_c^2\right)\overline{N}_{p2s} \qquad (41)$$

The particle deposition rates are given by:

$$R_{ps}^{\sigma} = k_d^{\sigma}\left(u_l c_{pl}\right)_{slurry} - k_e^{\sigma}\ \left(\in_s \rho_p\right)_c \left(\tau - \tau_{cr}\right)\ U\left(\tau - \tau_{cr}\right) \tag{42}$$

$$R_{p2s}^{\sigma} = k_{d2}^{\sigma}\left(u_l c_{p2l}\right)_{slurry} - k_{e2}^{\sigma}\ \left(\in_s c_{p2s}\right)_c \left(\tau - \tau_{cr2}\right)\ U\left(\tau - \tau_{cr2}\right) \tag{43}$$

$$\tau = k'\left(4v/r_c\right)^{n'} \tag{44}$$

$$\tau_{cr} = H\Big/\left(24dl^2\right) \tag{45}$$

$$\overline{R}_{p2s} = \overline{k}_d \overline{\in}_l \overline{c}_{p2l} - \overline{k}_e \overline{\in}_s \overline{c}_{p2s} \tag{46}$$

The filter cake and formation porosity and permeability variation considers

- Fluid drag effect on the cake compressibility
- Fine particle deposition in the cake and formation

Thus, the porosity and permeability relationships are given by:

$$\frac{\overline{\phi}}{\phi^o} = \left[1 - \alpha\left(\frac{\overline{\in}_{p2s}}{\phi^o}\right)^n\right]\left[\frac{1}{\phi^o} - \left(\frac{1}{\phi^o} - 1\right)\ \left(1 + \frac{\overline{p}_s}{p_a}\right)^{\beta}\right] \tag{47}$$

$$\overline{k}_c\Big/k_c^o = \left(1 + \alpha_1 \overline{\in}_{p2s}^{\alpha_2}\right)^{-1}\left(1 + \overline{p}_s/p_a\right)^{-\delta} \tag{48}$$

Forchheimer's equation considering non-Darcy flow is given by:

$$-\frac{\partial p}{\partial r} = \frac{\mu}{2\pi h K}\ \frac{q}{r} + \frac{\rho \quad \beta}{\left(2\pi h\right)^2}\ \left(\frac{q}{r}\right)^2 \tag{49}$$

A straight line plot indicates Darcy flow.

Case II-Deep-bed Filtration

Deep-bed Filtration model is given as follows (Herzig et al., 1970):
Transport Equation:

$$\phi\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} + \frac{\partial \sigma}{\partial t} = 0 \tag{50}$$

Deposition Rate:

$$\frac{\partial \sigma}{\partial t} = \lambda u c \tag{51}$$

Darcy's Law:

$$u = -\frac{K(\sigma)}{\mu}\frac{\partial p}{\partial x} \tag{52}$$

From the point of practical applications, several special cases may be considered (Pang and Sharma, 1995):

- Open-hole wells (Radial flow)
- Perforated wells (Ellipsoidal flow)
- Hydraulically-fractured wells (Elliptic flow)

Fines invasion and cake formation along the hydraulic fractures vary with locations. Therefore, the filter cake distribution varies with time as the filter cake thickness increases (Hofsaess and Kleinitz, 2001).

Case III- Near-wellbore damage (Civan, 2001)

Civan (2001) generalized the sulfur deposition model by Roberts (1997) for generalized applications as following.

Darcy's Law

$$u = \frac{qB}{2\pi hr} = \frac{K}{\mu}\frac{dp}{dr} \tag{53}$$

Sulfur solubility in natural gas is described by (Roberts, 1997):

$$H_2S + S_x \Leftrightarrow H_2S_{(x+1)}$$

$$c = \rho^4 \exp\left[-\frac{4,666.}{T} - 4.571\right] \tag{54}$$

Rate of precipitation

$$\frac{dV}{dt} = q\left(\frac{dC}{dp}\right)_T dp \tag{55}$$

Porosity reduction by deposition is given by, assume perfect ideal packing

$$\varepsilon = \phi_o - \phi \tag{56}$$

Permeability reduction by fractional deposit volume is expressed as:

$$K/K_o = \exp(-a\varepsilon) \tag{57}$$

Particle deposition equation is obtained as:

$$\frac{d\varepsilon}{dt} = \left(bq^2/r^2\right)\exp(a\varepsilon) \tag{58}$$

$$\varepsilon = 0, t = 0 \tag{59}$$

Dimensionless solutions are given by:

$$r_D{}^2 = \frac{\left[1-\exp(-a\phi_o)\right]\exp(-2s)}{\left[1-\exp(-a\varepsilon)\right]} t_D \tag{60}$$

$$\frac{K}{K_o} = 1 - \frac{\left[1-\exp(-a\phi_o)\right]\exp(-2s)}{r_D{}^2} t_D \tag{61}$$

Solution of these equations yield the transient-state deposit profiles (Civan, 2001).

Final Remarks

The review presented in this paper reveals that there are several topics of practical importance and areas needing further research:

- Improved formulations leading to prediction
- Consistent porous media averaging.
- Model-aided experimental measurement and correlation methods for direct determination of parameters.
- Effect of diffusion/dispersion on particle transport
- Non-equilibrium relaxation effects (Einstein, 1920, Civan, 2006)
- Multiple porosity and permeability porous media formulations (Naturally fractured

porous media).

- Rigorous constitutive equations.

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