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Determining model parameters for non-linear deep-bed filtration using laboratory pressure measurements

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A R T I C L E I N F O

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A B S T R A C T

Particle capture in porous media and the consequent permeability reduction occur in oilfields during water injection or produced water re-injection, migration of mobilized reservoir fines, and invasion of drilling and completion fluids into formations. Reliable modelling-based prediction of particle propagation in natural reservoirs is an essential step in the planning and design of waterflooding.

The mathematical model for suspension-colloidal transport in natural reservoirs contains two empirical functions of retained particle concentration. The filtration function expresses the particle capture rate. The formation-damage function determines the permeability decline due to particle capture and retention. Previous works developed an inverse-problem solution to recover both functions from breakthrough concentration and the pressure drop. The present paper develops a new method that determines the filtration and formation-damage functions from pressure measurements only. The method uses pressure data at an intermediate point of the porous column (core), which supplements pressure measurements at the core inlet and outlet. The proposed method furnishes two retained-concentration functions for filtration and formation-damage. The method is validated by comparison with laboratory experiments. A high fit with the pressure data at three core points was observed. Moreover, the fitted model predicts the pressure measured at other core points with high precision.

1. Introduction

Colloidal and suspension flows in natural reservoirs, where particle-capture by the rock matrix reduces permeability and thereby causes formation damage, can undermine numerous petroleum production processes. The above includes production of oil and gas that involves migration of fines, invasion of drilling and completion fluids into the formation, injection of nanoparticles in oil reservoirs, injection of water with solid and liquid particles into oilfields, produced water re-injection, and produced water disposal in aquifers (Sarkar and Sharma, 1990; Khilar and Fogler, 1993; Pang and Sharma, 1997; Schembre and Kovscek, 2005; Schembre et al., 2006; Fleming et al., 2007, 2010; Byrne and Waggoner, 2009; Byrne et al., 2014; Civan, 2014; Arab et al., 2014; Lagasca and Kovscek, 2014; Yuan et al., 2016). Particle capture yields rock clogging and decrease in well productivity and injectivity. Particle retention in the porous matrix occurs due to numerous physics mechanisms: attachment by electrical forces, size exclusion (straining), bridging, gravity, diffusion, and (Figs. 1 and 2).

Design and planning of the above-mentioned petroleum processes and technologies are based on mathematical modelling that account for well-known model parameters.

The mathematical model for deep bed filtration of natural and foreign fines consists of equations for balance of suspended and retained particles, rate for particle retention, and Darcy´s law modified to reflect permeability decline due to particle capture (Herzig et al., 1970; Tufenkji, 2007; Yuan and Shapiro, 2011a, 2011b):

$$\phi\frac{\partial c}{\partial t} + U\frac{\partial c}{\partial x} = -\frac{\partial \sigma}{\partial t}, \tag{1}$$

$$\frac{\partial \sigma}{\partial t} = \lambda(\sigma)cU, \tag{2}$$

$$U = -\frac{k(\sigma)}{\mu}\frac{\partial p}{\partial x}. \tag{3}$$

Here ϕ is the porosity, c is the volumetric concentrations of suspended particles, σ is the volumetric concentrations of retained particles, U is the Darcy´s velocity, μ is the viscosity, and p is the pressure. The filtration function $\lambda(\sigma)$ is the probability for particle capture per unit of the travel distance (Sharma and Yortsos, 1987; Bedrikovetsky, 2008; Yuan and Shapiro, 2011a,b). The retained-concentration dependence

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Nomenclature

Latin letters

A	specific rock surface $[L]^{-1}$, m^{-1}
b	area on grain surface filled by one retained particle $[L]^2$, m^2
c	volumetric suspension particle concentration
c_O	volumetric injected suspension concentration
J	impedance
k	permeability $[L]^2$, m^2
L	core length [L], m
n	formation-damage power
p	pressure $[M][T]^{-2}[L]^{-1}$, Pa
r	radius [L], m
t	time [T], s
U	Darcy velocity $[L][T]^{-1}$, m/s
V_O	volume of a single particle $[L^3]$, m^3
x	linear distance [L], m

Greek letter

β	formation-damage coefficient
λ	filtration coefficient $[L]^{-1}$, m^{-1}
μ	viscosity of water $[M][T]^{-1}[L]^{-1}$, kg/(s*m)
σ	deposited particle concentration
ω	dimensionless length of the first core section
ϕ	porosity

Super/subscripts

0	initial
D	dimensionless
m	maximum
w	well

for permeability $k(\sigma)$ is called the formation-damage function.

The model (1-3) contains two empirical (material) functions $\lambda(\sigma)$ and $k(\sigma)$. The filtration function $\lambda(\sigma)$ determines the particle-capture rate. The formation-damage function $k(\sigma)$ reflects the permeability decline due to particle retention (Herzig et al., 1970, Grenier et al., 2008). Knowledge of these two functions is indispensable for predicting suspension-colloidal transport in natural reservoirs.

The filtration and formation-damage functions reflect intrinsic properties of the rock-colloid system. The functions $\lambda(\sigma)$ and $k(\sigma)$ can be determined theoretically only for porous media that have simplified geometry. Determining these functions in a realistic setting requires experimental tests by flowing water that contains particles, through the reservoir cores (see the laboratory tests and the relevant data treatment in works by Al-Abduwani, (2005), Al-Abduwani et al. (2005), Bedrikovetsky et al. (2001) and Mays and Hunt (2007). Alvarez et al. (2006, 2007) show that both functions can be inferred from combined measurements of the differential pressure and the breakthrough concentration of suspended particles at the core effluent: $\lambda(\sigma)$ is determined from the breakthrough concentration, whereas $k(\sigma)$ is calculated from the pressure drop growth.

A coreflood test is usually accompanied by inlet and outlet pressure measurements. The pressure measurements are inexpensive and simple to perform, and therefore widely employed (Todd et al., 1984; Soo and Radke, 1986; Nabzar et al., 1996; Chauveteau et al., 1998; Moghadasi et al., 2004; Civan, 2014). In contrast, measurement of breakthrough concentration requires cumbersome procedures with special equipment; it provides lower accuracy than pressure drop measurements. These difficulties motivate the development of methods for determining functions $\lambda(\sigma)$ and $k(\sigma)$ from pressure measurements only (Bedrikovetsky et al., 2001).

The case of low retained particle concentrations, where the number of captured particles is negligible compared to the number of the vacant pores ($\sigma << h$), corresponds to the constant filtration function $\lambda(\sigma)=const$ and the hyperbolic formation-damage function (Pang and Sharma, 1997)

$$k(\sigma) = \frac{k_0}{1 + \beta\sigma}, \tag{4}$$

where k_O is the initial permeability and the constant β is so-called formation-damage coefficient. Dependency (4) follows from Taylor´s series for the normalized reciprocal $k_O/k(\sigma)$ with respect to small σ, keeping zeroth-order and first-order terms.

For the case of constant filtration and formation-damage coefficients, the ratio between the differential pressure across the core and the flow rate grows linearly with respect to injected water volume (Pang and Sharma, 1997). We will denote the low-retention case as linear clogging, the constant value λ as the filtration coefficient, and the constant β as the formation-damage coefficient.

The so-called 3-point-pressure method allows determining two constants λ and β from the pressure measurements at an intermediate point of the core, as well as at the core entrance and outlet during deep-bed-filtration coreflooding (Bedrikovetsky et al., 2001). Fig. 3 shows the schematic of the 3-point-pressure test. The slopes of two linear dependencies of differential pressure across the overall core and the first core section are used for determining two constants. The method includes an inverse problem that provides unique values for constants λ and β. The inverse solution is stable with respect to small perturbations of the measured pressures.

However, numerous laboratory tests have exhibited non-linear differential pressure versus time, i.e., non-linear clogging occurs (Al-

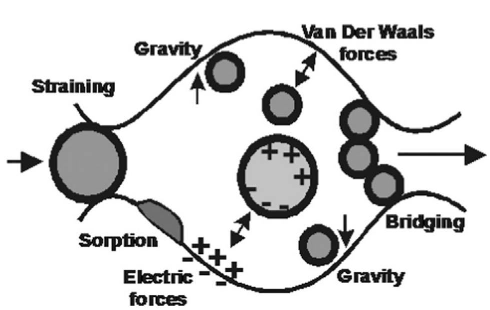

Fig. 1. Schematic for multiple particle-capture mechanisms in pore space during seawater injection.

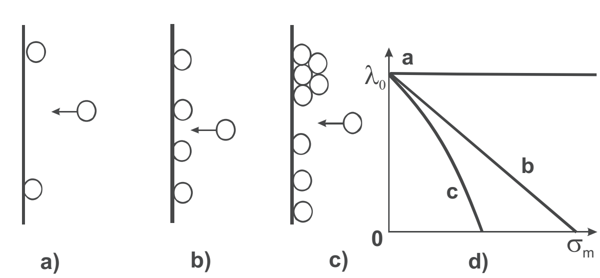

Fig. 2. Various forms of filtration function for different retention concentrations: a) low retention concentration does not change the particle attachment conditions, thus the capture probability is constant; b) the particle capture rate is proportional to vacancy concentration for medium retention concentration, so the filtration function is a linear function of attached concentration; c) the particles interaction causes the restriction for deposition on vacant sites at high retention concentrations; mono-layer and poly-layer sorption occur simultaneously; the filtration function is non-linear; d) different forms of filtration function.