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Slow migration of mobilised fines during flow in reservoir rocks: Laboratory study

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ABSTRACT

Permeability decline during high rate flows has been widely reported for corefloods and for production wells. The phenomenon is attributed to mobilisation of fine particles at elevated velocities, their migration in porous space with the following straining in thin pores and attachment to pore walls. Sixteen sets of corefloods with piecewise constant rate have been performed under increasing flow rate. The particularities of this study are long injection periods, allowing estimating permeability stabilisation times, and pressure measurements in intermediate core points, permitting for evaluation of the permeability profile variation along the core. It was found out that the mobilised particles drift with speeds significantly lower than the carrier fluid velocity, resulting in long permeability stabilisation periods.

1. Introduction

Detachment of the reservoir fines, their migration as colloids or suspensions in the carrier fluid with further straining in thin pore throats and attachment to pore walls occur in numerous petroleum production processes. The main features of the processes are the variation of colloidal suspension concentration in carrier fluid, which is important for produced water disposal in aquifers, and the permeability decline affecting well productivity and injectivity (Civan, 2007; Rousseau et al., 2008; Byrne and Waggoner, 2009). The above occurs during filtrate invasion into reservoirs during well drilling (Schechter, 1992; Watson et al., 2008), fines migration in oil and gas reservoirs (Schembre and Kovscek, 2005; Civan, 2007) and low quality water injection into oilfields (Nabzar et al., 1996; Pang and Sharma, 1997; Chauveteau et al., 1998). The role of fines migration during low-salinity waterflooding of oil reservoirs is a subject of the current intensive research (Tang and Morrow, 1999; Morrow and Buckley, 2011; Zeinijahromi et al., 2011; Yuan and Shapiro, 2011; Hussein et al., 2013). The permeability reduction due to fines migration can be used for water production control (Zeinijahromi et al., 2012). The list of fines migration applications can be significantly expanded.

The common view on the flow of mobilised fines in porous reservoirs is that the fine colloidal or suspension particles are transported in the carrier fluid. It means that the advective velocity of particles is equal to the carrier fluid velocity; the permeability stabilisation occurs after arrival of the “last” mobilised fine at the core outlet, i.e. after the injection of one pore volume. Several authors have mentioned the two-speed structure of the colloidal suspension flux, where the particles may undergo the near-surface motion with significantly reduced speed if compared to the carrier water velocity (Yuan and Shapiro, 2010). The particle drift near the rough pore walls as modelled by Navier–Stokes equations has the speed significantly lower than the injected water velocity (Sefriouri et al., 2013). However, the vast majority of mathematical models assume equality of particle and water velocities (Bradford et al., 2008, 2009). Besides, laboratory studies of slow fine particle migration in porous media are not available in the literature.

Several laboratory corefloods with increasing velocity in order to lift fines have been performed, yielding the clear understanding of mobilisation and straining phenomena (Priisholm et al., 1987; Ochi and Vernoux, 1998; Kuhn et al., 1998, etc.). The detailed overviews of those works are presented by Tiab et al. (2004) and Civan (2007). Yet, the permeability stabilisation periods cannot be evaluated from the results of these tests due to short injection times. Also, the permeability profile cannot be evaluated since only the pressure drop across the overall core has been measured.

In the current work, the corefloods with piecewise constant velocity in the mode of velocity increase in order to lift the natural

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reservoir fines are performed until the permeability stabilisation. It is found out that the permeability stabilisation periods significantly exceed one pore volume injected in all the tests, while the assumption of equality of particle and water velocities yields the stabilisation after injection of one pore volume. The delayed stabilisation is attributed to slow fines transport near pore walls. The stabilisation time decreases with the flow rate increase, which is explained by simultaneous increase of drag force driving the particles along the rock surface.

The structure of the paper is as follows. Brief physical description of colloidal suspension transport in porous media is given in Section 2. Section 3 presents the details of the laboratory set-up, rocks and fluids used and the methodology of laboratory tests. The test results are presented in Section 4. The paper is concluded by the discussions of results (Section 5), where the observed phenomena of delayed permeability stabilisation are attributed to the slow particle drift along the rock surface.

2. Physics of fines mobilisation, migration and straining

Following Muecke (1979), Sharma and Yortsos (1987), Chauveteau et al. (1998), Bergendahl and Grasso (2000), Freitas and Sharma (2001), Byrne et al. (2010), Bradford et al. (2011) and Bedrikovetsky et al. (2011, 2012), let us describe the main physical factors determining fines migration with consequent permeability decline in porous media. Detachment of fine particles, their migration with followed straining or attachment is shown in Fig. 1. The mobilised fine particle is retained by size exclusion if its size exceeds the pore size (Yuan et al., 2012; You et al., 2013). The fine particle intercepting a grain can also be attached, if there are available attachment sites on the grain surface. The forces exerting upon a single particle attached to the grain are shown in Fig. 1. The particle on the grain surface or on top of the internal cake formed by other attached particles is subject to electrostatic, drag, lifting and gravitational forces. The particle is attached if the attaching torque of electrostatic force and gravity exceeds the detaching torque of drag and lifting forces; otherwise the particle leaves the grain surface. The torque equilibrium is the condition of the particle mechanical equilibrium. The electrostatic force depends on the grain–particle disjoining distance that reaches the maximum at certain disjoining distance value. For the given values of drag, lifting and electrostatic forces, particle mobilisation is controlled by the maximum value of the attractive electrostatic force. If the attaching torque exceeds the detaching torque, the disjoining distance is determined by the torque balance under given values of drag, lifting and electrostatic torques. From the torque balance criterion follows that under the mechanical equilibrium, there does exist the maximum concentration of retained particles that is a function of carrier fluid velocity, salinity, pH, temperature, etc. Particle detachment due to velocity, pH or temperature increase or salinity decrease is described by the maximum retention function decrease. Velocity increase yields an increase of drag and lifting forces; it may raise the detaching torque resulting in the particle mobilisation. The water salinity decrease causes a decrease of the electrostatic force with consequent decrease of the attaching torque and fines mobilisation. Increase of temperature and pH also causes weakening of electrostatic force with consequent fines mobilisation. The above phenomena of fines mobilisation by increasing velocity have been observed and discussed in laboratory studies by Miranda and Underdown (1993), Ochi and Vernoux (1998), Bradford et al. (2011), while the fines lifting due to salinity decrease or temperature and pH increase is presented by Lever and Dawe (1984), Sarkar and Sharma (1990), Valdya and Fogler (1992), Khilar and Fogler (1998) and Civan (2010).

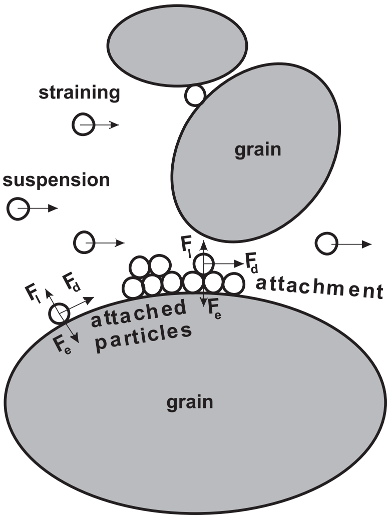

Fig. 1. Fine particles detachment from grains, migration in carrier water, attachment to grains and straining in thin pores.

The classical filtration theory introduces critical velocity as the minimum velocity, where fines mobilisation occurs (Miranda and Underdown, 1993). Critical salinity is the salinity threshold below which the fines are lifted (Khilar and Fogler, 1998). The particle detachment rate is proportional to the difference between the current and critical values of velocity, salinity, pH, etc. The proportionality coefficients correspond to relaxation times, which are empirical coefficients and are obtained from the fitting. The model exhibits the delay in permeability response to an abrupt change of the parameters, while several laboratory studies reveal an instant permeability response (Lever and Dawe, 1984; Ochi and Vernoux, 1998; Bedrikovetsky et al., 2012). The above mentioned model of maximum retention function is free of this shortcoming.

If the migrating particle intercepts the grain and the attaching torque exceeds the detaching torque, the particle becomes attached to the grain. The size exclusion mechanism of the particle has been mentioned before. Another mechanism of particle retention is diffusion into the dead-end pores, where the particles may remain not being accessible to the flow in skeleton pores. In the next section we present the methodology and set-up of the laboratory study of fines mobilisation under increasing flow velocity followed by migration and capture.

3. Laboratory study

In this section we describe laboratory set-up (Section 3.1), characteristics of rock and fluids (Section 3.2) and methodology of flow testing under alternate velocities (Section 3.3).

3.1. Set-up

The schematic of laboratory set-up with specification of all key elements is shown in Fig. 2. Fig. 3 is the photo of set-up. The injected fluid is placed in Beaker 1 and is injected by PU-2087 pump Jasco under constant rate. The core-holder Mantec (Labconte) with two intermediate ports for pressure measurements is controlled by valves 14 and 15. The overburden pressure in core-holder is provided by manual pump Fluke 10 and is monitored by manometer 11. Pressure transducers 5, 6 and 7 measure pressure drops across the overall core, between the entrance and second ports and across the first core section, respectively. The Yokogawa transducers are calibrated to measure the pore pressure from zero to 500 psi. The data acquisition system 8 delivers a digital form for