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Deep bed and cake filtration of two-size particle suspension in porous media

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ABSTRACT

Formation of low permeable external filter cake during drilling and water injection has been widely reported in the literature. It may cause significant decrease in well index. The process is very sensitive to size distribution of injected particles. We propose a new mathematical model for cake formation with deep bed filtration for two-particle-size injection. The basic equations account for three stages: formation of cake from large particles with simultaneous deep bed filtration of small particles; small particle capture in the cake with formation of the internal cake inside the external cake; build-up of the uniform cake from the mixture of two-size particles. The analytical model is derived for three stages. Two regimes of the cake formation are identified, which correspond to the high and low concentrations of injected small particles. The laboratory coreflood with two-particle-size suspension injection with monitoring the rate and pressure drop along the core is performed. The matched mathematical model shows good agreement with the laboratory data.

1. Introduction

Deep bed filtration and external filter cake formation are common phenomena encountered in the petroleum industry, which may lead to severe permeability decline and formation damage (Ghalambor and Economides, 2002; Ding et al., 2004; Ding and Renard, 2005; Ding et al., 2006; Wagner et al., 2006; Civan, 2007; Dalmazzone et al., 2007; Quintero et al., 2007; Ding et al., 2008; Salimi et al., 2009; Lohne et al., 2010; Karimi et al., 2011). During drilling, completion or produced water reinjection, fluids carrying suspended particles enter the wellbore. Due to the pressure difference between the wellbore and the reservoir formation (the pressure in the well is higher than that of the formation during the overbalanced drilling), the fluid penetrates into the formation. Particles suspended in the fluid with sizes larger than the pore throats in the formation may accumulate on the wellbore surface, forming a cake. This process is known as the external cake formation (Ruth, 1935; Ochi et al., 1999; Parn-anurak and Engler, 2005; Ochi et al., 2007; Windarto et al., 2011; Ytrehus et al., 2013). However, those fine particles smaller than the pore throats of external cake may pass through the cake and penetrate into the formation. During the filtration, the solid particles suspended in the carrier fluid may be separated from the liquid phase due to several different mechanisms, such as gravity, Brownian motion, size exclusion, etc. (Ochi and Vernoux, 1999; Shapiro et al., 2007; Yuan and Shapiro, 2011; You et al., 2013; Yuan et al., 2013). The process of suspension transport in porous media accompanied by particle capture in the pores is called deep bed filtration (Payatakes et al., 1974; Pang and Sharma, 1997; Khilar and Fogler, 1998; Bedrikovetsky, 2008; You et al., 2014).

The classical deep bed filtration (DBF) model developed by Herzig et al. (1970) consists of two equations—one for particle population balance and the other for particle capture kinetics. The macro scale functions including suspended and retained particle concentrations and the filtration coefficient as a function of retained concentration are introduced into the model. Analytical solutions to the direct problems for model prediction (Herzig et al., 1970) and to the inverse problems for parameter determination (Wennberg and Sharma, 1997; Bedrikovetsky et al., 2001) have been obtained. This model has shown a good agreement with experimental data and has been used to predict the well injectivity decline based on the experimental core flood data.

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Nomenclature

L	core length, m
r_s	small particle radius, m
r_l	large particle radius, m
c_1^0	initial total particle concentration, ppm
c_2^0	initial large particle concentration, ppm
c_3^0	initial small particle concentration, ppm
D_p	particle diameter, m
D_3	speed of mixture cake growth
J	impedance
$k_m(0)$	initial core permeability, m^2
k_{ec12}	permeability of external cake filled by internal cake of small particles, m^2
R	ratio of external cake porosity and core porosity
ΔP_{ec1}	pressure drop between the fronts of external and internal cake, Pa
ΔP_{ec2}	pressure drop between the front of internal cake and the core inlet, Pa
ΔP_m	pressure drop of the core, Pa
S	dimensionless retention concentration
U	Darcy velocity, m/s
T	dimensionless time
t	time, s
T_{tr}	transition time
T_3	catching-up time of the internal cake front
X	dimensionless coordinate
x	coordinate, m
z	internal cake thickness, m

Greek letters

α	critical coefficient
β	formation damage coefficient
λ	filtration coefficient
μ	viscosity of suspension, Pa s
τ	tortuosity
ϕ_1	core porosity
ϕ_2	porosity of internal cake
ϕ_3	porosity of external cake
ϕ_4	porosity of the mixture cake
σ	retained particle concentration, m^{-3}

Subscripts

m	medium
c	cake
ec	external cake
ecmix	mixture cake

Analytical models for deep bed filtration with constant and varying rates for linear and axisymmetric flows have been derived by Civan and Rasmussen (2005). Numerous laboratory tests have been treated by the analytical model with the observation of good agreement between the analytical and experimental modelling. More complex model for deep bed filtration is proposed by Civan and Nguyen (2005). All pathways are divided into two parts—those plugging and non-plugging. The analytical models as well as their tuning by laboratory tests have been performed.

During particle deep bed filtration through porous media, there exists a critical moment when the retention concentration of particles at the core inlet reaches its critical value (Khatib, 1994). After the moment, few particles can penetrate into the core. Instead, the new-coming particles form external cake only. This critical moment is termed as the transition time. The existence of transition time has been observed and its evaluation has been studied intensively (Ochi et al., 1999; Zitha et al., 2013). The phenomenon of particle deep bed filtration followed by the formation of external filter cake is not described in the above classical DBF models (Tien, 2012).

Moreover, the oversimplified DBF model using the overall particle concentrations does not account for the effect of pore and particle size distributions on permeability decline in field cases (Veerapen et al., 2001; Massei et al., 2002; Windarto et al., 2012). Glenn and Slusser (1957) reported that certain distribution of particle sizes may reduce the permeability impairment for a given pore size distribution, i.e., the particle size distribution must be accounted for in the cake formation model. Corapcioglu and Abboud (1990) developed a model for cake filtration process accounting for different size particle penetration at the cake surface and migration in the cake. Furthermore, the compressibility effect of the external cake is taken into account with the modelling of the cake growth dynamics considering cake filtration (Sherwood and Meeten, 1997; Tien et al., 1997; Lohne et al., 2010). Civan (1998a, 1998b) investigated cake formation and stabilisation for cross flow filtration. The kinetics model accounts for erosion rate, which is proportional to the difference between the critical and current values of the shear stress. Non-Newtonian fluid properties are taken into account. The analytical models have been derived. Good agreement between the modelling and experimental data has been observed for both linear and radial flows.

The traditional model presents a linear growth of pressure drop over time along the core and its abrupt increase during the external filter cake formation. It results in the delay of external cake formation if compared to particle penetration into the rock. The growth of internal cake formed by the fine particles inside the external cake after the transition time is not accounted for in the models for either drilling fluid invasion or water injectivity (Pang and Sharma, 1997; Wennberg and Sharma, 1997; Suri and Sharma, 2004; Bedrikovetsky et al., 2005). So, the above models assume DBF occurring before the transition time and build-up of external cake afterwards. Yet, in practice, a significant fraction of particles in drilling fluid exceeds pore sizes, so the formation of external cake starts at the beginning of injection, simultaneously with fine particle DBF (Abrams, 1977; Hands et al., 1998; Massei et al., 2002; Tien, 2012).

To the best of our knowledge, the mathematical model for cake filtration that accounts for co-occurring deep bed filtration and cake formation as well as internal cake formed by small particles inside the external cake by large particles is not available in the literature.

The present work aims to partly fill the gap considering injection of bi-sized suspension in the rock. The large particles start building the cake at the beginning of injection; while the small particles simultaneously filtrate through the built-up cake and penetrate into the porous media. After the transition time, the small particles filtrate in the external cake only. The aim of the present work is to develop a mathematical model for cake filtration (i.e. cake formation and deep bed filtration), including the external cake formation by large particles, DBF of small particles, internal cake growth inside external cake after the transition time, and possible formation of mixture cake after the catching-up time. Besides, the laboratory experiments on the injection of bi-sized suspension into a reservoir core have been performed. The results obtained from the proposed model match the laboratory data with high accuracy, which validates the model proposed.

The structure of the paper is as follows. First, the traditional deep bed filtration and cake formation model for mono-size particles is