
# Advanced Analytical Models for Well Injectivity Decline

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*To my Mum and Dad,*

*to my Wife,*

*to my lovely daughters Tahoora*

*and Zahra* ( *I lost her during preparation of this thesis*)

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# Abstract

The major fraction of world oil is produced by waterflooding, where the injected water displaces oil and maintains the reservoir pressure. In addition, produced water reinjection (PWRI) is an economic and environmental-friendly option to convert waste to value with waterflooding. However, the major challenge is the drastic decline of well injectivity which has been widely reported in the literature. The main mechanisms of the injectivity decline are capture of particles from injected water in the porous rock and formation of low permeable external filter cake on the well wall followed by its stabilisation. The reliable predictive analytical model for well injectivity behaviour forecast up to the stabilisation stage is not available in the literature.

So, the aim of this thesis is to develop full predictive analytical models for injectivity decline during sea water injection and PWRI.

In order to achieve this aim, a new mathematical model for injectivity stabilisation using mechanical equilibrium of a particle on the cake surface accounting for all colloidal forces is developed in this thesis. It is found that the main empirical parameter of the model, highly affecting the stabilised cake prediction, is the lever arm ratio. The lever arm ratio is calculated from laboratory cross-flow filtration experiments and from well injectivity data. It is also determined from Hertz's theory for the elastic particle deformation. Good agreement between the calculated results for the lever arm ratio validates the developed model.

This thesis presents the derivation of a new analytical model for non-uniform cake thickness profile along injection wells. It is found out that, two regimes of the stabilised cake build-up correspond to low injection rates, where the cake starts from the reservoir top, and for high injection rates, where the cake is formed only on the lower well section. The sensitivity analysis shows that water injection rate, cake porosity, water salinity and Young's modulus are the most influential parameters defining the cake thickness profile.

The thesis presents the development of an analytical model for axi-symmetric two-phase flow with simultaneous deep bed filtration of injected particles, formation of external filter cake and its stabilisation due to particle dislodgement. It also introduces a seven-parameter adjustment method. It is shown that the initial injectivity increase,

induced by varying two-phase mobility, adds three degrees of freedom to one-phase impedance growth model. This additional information is used to tune the models with the Corey relative permeability and the pseudo relative permeability under the viscous-dominant displacement. Good agreement between field data and model prediction validates the developed analytical model for injectivity decline during waterflooding and its adjustment method.

The developed analytical model along with laboratory coreflood test data and probabilistic histograms of injectivity damage parameters are applied to predict the injectivity behaviour during produced water disposal into a thick low preamble sandstone reservoir as a field case study. Unusual convex form of impedance curve is observed in the coreflood test and well behaviour modelling; impedance grows slower during external cake formation if compared with deep bed filtration. Risk analysis method using probabilistic histograms of injectivity damage parameters is also developed and applied to well behaviour prediction under high uncertainty conditions.

The above analytical models, results of laboratory studies and field cases allow recommending the developed models for full prediction of injectivity decline during waterflooding and disposal operations.

# Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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Azim Kalantariasl Date

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# Publications

### Peer reviewed journal publications

1. **Kalantariasl, A.,** Bedrikovetsky, P. (2013) Stabilization of External Filter Cake by Colloidal Forces in a "Well-Reservoir" System, *Industrial & Engineering Chemistry Research*, **53**(1), 930-945.
2. **Kalantariasl, A.,** Zeinijahromi, A., Bedrikovetsky, P. (2014) Axi-Symmetric Two-Phase Colloidal-Suspension Flow in Porous Media during Water Injection, *Industrial & Engineering Chemistry Research*, **53**(40), 15763-15775.
3. **Kalantariasl, A.,** Zeinijahromi, A., Bedrikovetsky, P. (2014) Modelling of External Filter Cake Profile along the Well during Drilling, *Australian Petroleum Production and Exploration Association (APPEA) Journal*, **54**, 319-328.
4. **Kalantariasl, A.,** Farajzadeh, R., You, Z., Bedrikovetsky, P. (2015) Non-Uniform External Filter Cake in Injection Wells, *Industrial & Engineering Chemistry Research*, **54**(11), 3051-3061.
5. **Kalantariasl, A.,** Schulze, K., Storz, J., Burmester, C., Küenckeler, S., You, Z., Badalyan, A., Bedrikovetsky, P. (2015) Produced Water Re-Injection and Disposal in Low Permeable Reservoirs, *Petroleum Science and Engineering*, (under review, Manuscript: PETROL-S-15-00103).

### International conference papers and poster presentations

6. **Kalantariasl**, **A.,** Duhan, S., Bedrikovetsky, P. (2013) Type Curves for Injectivity Decline, presented at *SPE European Formation Damage Conference & Exhibition*, Noordwijk, The Netherlands, 5-6 June, SPE 165112-MS.
7. **Kalantariasl, A.,** Zeinijahromi, A., Bedrikovetsky, P. (2014) External Filter Cake in Dynamic Filtration: Mechanisms and Key Factors, presented at *SPE International Symposium and Exhibition on Formation Damage Control*, Lafayette, Louisiana, USA, 26-28 February, SPE 168144-MS.
8. **Kalantariasl, A.,** Zeinijahromi, A., Bedrikovetsky, P. (2014) External Filter Cake Formation: Experience from Membrane (Micro/Ultra/Nano) Filtration, presented at *SPE workshop "Nano-Technology and Nano-Geoscience in Oil and Gas Industry"*, Kyoto, Japan, 4-7 March.

9. **Kalantariasl, A.,** Zeinijahromi, A., Bedrikovetsky, P. (2014) Modelling of External Filter Cake Profile along the Well during Drilling, presented at *Australian Petroleum Production and Exploration Association (APPEA) Conference and Exhibition*, Perth, Western Australia, Australia, 6-9 April.
10. **Kalantariasl, A.,** Farajzadeh, R., You, Z., Bedrikovetsky, P. (2015) Mathematical Modelling of Non-Uniform External Filter Cake in Long Injection Wells, presented at *SPE European Formation Damage Conference & Exhibition*, Budapest, Hungary, 3-5 June, 2015, SPE-174184-MS.
11. **Kalantariasl, A.,** Schulze, K., Storz, J., Burmester, C., Küenckeler, S., You, Z., Badalyan, A., Bedrikovetsky, P. (2015) PWRI and Disposal in a Thick Tight Formation (Mathematical Modelling, Laboratory Test and Field Case), presented at *SPE European Formation Damage Conference & Exhibition*, Budapest, Hungary, 3-5 June, SPE-174185-MS.
12. **Kalantariasl, A.,** Bedrikovetsky, P. (2015) Formation Damage due to Drilling and Completion: External Cake Formation and Stabilisation, accepted for presentation at *SPE Russian Petroleum Technology Conference*, Moscow, Russia, 26-28 October, SPE-176527-MS.

**Publications in preparation**

1. **Kalantariasl, A.,** Bedrikovetsky, P. (2015) Type Curves for Injectivity Decline, to be submitted to journal of *Oil and Gas Science and Technology*.
2. **Kalantariasl, A.,** You, Z., Bedrikovetsky, P. (2015) Injectivity Decline in Limited Reservoirs, to be submitted to journal of *Petroleum Science and Engineering*.