The Experimental and Theoretical Study of Fines Migration in Porous Media under Particle-rock Repulsion and Attraction

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A thesis submitted for the degree of Doctor of Philosophy (PhD)

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Table of Contents

Abstract

This is a PhD thesis by publication. The essence of the research performed has been published in one book chapter, five journal papers and four SPE papers.

The thesis contains laboratory study of deep bed filtration in porous media accounting for particle migration, mobilization and straining for two particular cases: straining-dominant particle capture and filtering under high flow velocities.

Advanced *challenge core flood test* methodology to determine pore throat size distribution *under unfavorable particle retention conditions* is designed and developed in the thesis. It includes significant advance in design of the laboratory set-up if compared with previous version, development of the test procedures to provide the particle-rock repulsion and measure the *post-mortem* retention profile, analysis of accuracy and uncertainties of the experiments.

In more details, the improvements of the laboratory set-up and procedures include sieving of glass beads in the ultrasonic bath with consequent reduction of the sieving time and more reproducible grain size distribution, application of the dual syringe pump system with continuous injection of suspension and pulseless delivery of particles in the porous medium, measurements of the retention profile after the test by cutting up the porous column in 4-6 pieces and dispersing the material in water. The above methods are applicable to continuous as well as to a pulse type particle injection. Latex particle have been injected into packed glass beads or borosilicate filters at different concentrations, velocities, pH, and salinities. However, main varying parameters are size distributions of injected latex particles and compacted glass beads. The tests show that the pore throat size distributions can be recovered from the challenge tests.

Another development of the thesis includes deep bed filtration investigation under *high flow velocities under favorable particle retention conditions*. It includes the design of laboratory set-up, development of the experimental methodology to reveal the hysteretic phenomena of the particle attachment and detachment under high velocities, treatment of the data using the Forchheimer law of high velocity flow in rocks and formulating the modified Forchheimer law under the conditions of formation damage, development of the methodology for estimates of the accuracy and uncertainties of the performed laboratory high-velocity tests.

In more details, high velocity suspension flow in engineered porous medium was studied at various volumetric flow rates and conditions favorable for particle attachment under the occurrence of the phenomena of particle deposition, mobilization, migration and entrainment. The maximum retention function (the critical particle retention concentration) derived is a quadratic function of flow velocity. A strong particle surface attraction as indicated by calculation of DLVO energy potential, translates to almost a quarter of filter surface coverage by the attached particles. The particles can't be removed by an increase of solution velocity only due to strong particle-matrix attraction. The removal of approximately 17.5 % of the attached particles was achieved only after the reduction of salinity and increase in pH of solution at maximum velocity.

The work includes the development of the Forchheimer model for the case of particle retention, i.e. the advanced formula for inertial coefficient versus retained concentration is proposed. Application of the Forchheimer law to the laboratory data results in the formation damage coefficient dependency of the critical retained concentration and the inverse dimensionless function of velocity. The inertial coefficient showed similar behavior at low velocities, although it remained almost constant at low surface coverage. Partial formation of the external cake on the inlet surface of the filter was observed by a

post-experimental examination using an optical microscope and via an abrupt increase in the formation damage and inertial coefficients during particle deposition at lower velocities. The partial cake coverage is the indication of the continuation of deep bed filtration even at high surface coverage which is supported by high filtration coefficient values at lower velocities. Results from the theoretical micro scale model based on the torque balance exerted on attached fine particles agree well with the experimental critical retention concentration data within combined standard uncertainties in the entire range of velocities. It allows proposing the model with modified Forchheimer flow equation and micro scale based maximum retention function for high velocity colloidal flows in porous media.

Statement of Originality

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published by or written by another person, except where due reference has been made in the text.

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In my daily work I have been blessed with a friendly and cheerful group of fellow students at Australian School of Petroleum. Thanks to all for welcoming and helping. I deeply appreciate ASP for providing all the equipments I needed to accomplish my thesis.

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Thesis by Publications

Book Chapter

1. **Aji K.**, Badalyan A., Carageorgos T., Zeinijahromi A., Bedrikovetsky P. *High Velocity Colloidal Flow in Porous Media: Experimental study and modeling*, in: Focus on Porous Media Research, Ed. by Zhao C, 2013, Nova Science Publishers, NY.

Peer Reviewed Publications

2. **Aji K.** *Particle deposition and mobilization during deep bed filtration in oil field.* International Journal of Oil, Gas and Coal Technology. Accepted on 31.06. **2013**. (http://www.inderscience.com/info/ingeneral/forthcoming.php?jcode=ijgct)

3. Badalyan A., You Z, **Aji K.**, Bedrikovetsky P., Carageorgos T., Zeinijahromi A. *Size exclusion deep bed filtration: experimental and modelling uncertainties.* Review of Scientific Instruments. V. 85, 015111.**2014**.

4. **Aji K.** *Experimental study of colloidal flow in porous media at high velocities.* Asia-Pacific Journal of Chemical Engineering. DOI: 10.1002/apj.1782.**2013**.

5. **Aji K.**, You Z., Badalyan A. *Transport and straining of suspensions in porous media: experimental and theoretical study*. Thermal Science. **2012**, 16(5), 1444-1448.

6. Badalyan A., Carageorgos T., Bedrikovetsky P., You Z., Zeinijahromi A., **Aji K**. *Critical analysis of uncertainties during particle filtration*. Review of Scientific Instruments, 83, 095106/1-9. **2012.**

SPE (Society of Petroleum Engineering) Papers

7. McLindin C., Saha A., Le K., **Aji K.**, You Z., Badalyan A., Bedrikovetsky P. *Colloidal flow in aquifers during produced water disposal: experimental and mathematical*

modelling. SPE-153502-MS. SPE Middle East Health, Safety, Security, and Environmental Conference, 2-4 April **2012**, Abu Dhabi, UAE. DOI: 10.2118/153502-MS.

8. You Z., **Aji K.**, Badalyan A., Bedrikovetsky P. *Effect of nanoparticle transport and retention in oilfield rocks on the efficiency of different nanotechnologies in oil industry.* SPE-157097-MS. SPE International Oilfield Nanotechnology Conference, 12-14 June **2012**, Noordwijk, The Netherlands. DOI: 10.2118/157097-MS. ISBN: 978-1-61399-206-7.

9. **Aji K.**, You Z., Badalyan A., Bedrikovetsky P. *Study of particle straining effect on produced water management and injectivity enhancement.* SPE-157399-MS. SPE International Production and Operations Conference & Exhibition, 14-16 May **2012**, Doha, Qatar. DOI: 10.2118/157399-MS. ISBN: 978-1-61399-201-2.

10. **Aji K.**, McLindin C., Saha A., Le K., You Z., Badalyan A., Bedrikovetsky P. *Colloidal-suspension flow in rocks: a new mathematical model, laboratory study, IOR.* SPE-152025-MS, The 2012 SPE EOR Conference at Oil and Gas West Asia, 16-18 April 2012, Muscat, Oman. DOI: 10.2118/152025-MS. ISBN: 978-1-61399-199-2.

Statement of Authors' Contributions

This thesis comprises a portfolio of ten publications that have been published, accepted for publication and/or submitted for publications in accordance with 'Academic Program Rules and Specifications 2012'. All journals to which the papers have been submitted are indexed in the 'ERA 2012 Journal List' database. The research summarized in the papers that constitute this thesis was undertaken within 'Formation Damage and EOR Research Group' at Australian School of Petroleum and with other universities and industry collaborators. Hence all the papers presented herein are co-authored and detail statements of relative contributions are endorsed by the co-authors.

Statement of Authorship

Title of Paper	Transport and straining of suspensions in porous media: experimental and theoretical study
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Publication Details	Aji K., You Z., Badalyan A. Transport and straining of suspensions in porous media: experimental and theoretical study. Thermal Science. 2012, 16(5), 1444-1448.

Author Contributions

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