Analytical Modelling of Fines Migration in Porous Media

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To

my wife, Yang

who has been a constant source of support and encouragement during the challenges of my study and life,

and my mum and dad, who have always loved me unconditionally.

I am truly thankful for having you in my life.

Table of Contents

Abstract .... **iii**

Declaration .... **vi**

Acknowledgment .... **vii**

Thesis by Publication .... **ix**

1 Contextual Statement **1**

1.1 Thesis structure 5

1.2 How the publications are related to the thesis 8

1.3 References 13

2 Literature Review **15**

2.1 Introduction 15

2.2 Fines migration in natural reservoirs 16

2.3 Governing equations 18

2.3.1 Traditional kinetics model *19*

2.3.2 Mechanisms of fines detachment *20*

2.3.3 The maximum retention function *27*

2.3.4 Release delay effect of attached particles *39*

2.4 Analytical solutions for constant filtration and formation damage coefficient 40

2.5 Summary 47

2.6 References 48

3 Analytical modelling of fines migration in porous media **53**

3.1 Slow migration of mobilised fines during flow in reservoir rocks: Laboratory study 54

3.2 Slow migration of detached fine particles over rock surface in porous media 65

3.3 Fines mobilisation by low-salinity water injection: 3-point-pressure tests…….. 117

3.4 Fines migration in aquifers and oilfields: laboratory and mathematical modelling 131

4 Mathematical modelling of fines migration in geothermal reservoirs.........210

5 Laboratory-based mathematical modelling of graded proppant injection in CBM reservoirs 224

6 Deep bed and cake filtration of two-size particle suspension in porous media….. 243

7 Conclusions...256

Abstract

Hereby I present a PhD thesis by publications. Altogether, the thesis includes: a) five journal papers, b) one book chapter, and one c) SPE conference paper. Five journal papers have already been published. The journal publication list includes high-impact-factor academic journals: *International Journal of Coal Geology*, *Geothermics*, *Journal of Natural Gas Science and Engineering*. The list also includes *Journal of Petroleum Science and Engineering*, which is a major academic journal in petroleum industry. I have also submitted one book chapter to be edited by Springer. Besides, the content of this thesis is published in six full-volume SPE technical papers of Society of Petroleum Engineering.

The thesis presents *new analytical models for fines migration in porous media*. The novelty of this work is the new governing equation system accounting for two effects during fines migration in rocks: slow drift of mobilised fines along rock surface, and the delayed release of fine particles (non-equilibrium effect).

Migration of fine particles in natural reservoirs is one of the main causes for formation damage in oil and gas fields. Numerous laboratory observations show that permeability stabilisation time is much longer than one pore volume injected. However, the existing mathematical models for fines migration, which are widely used in petroleum reservoir simulation, cannot predict the long-term stabilisation phenomenon.

The new analytical solutions derived in this thesis successfully model the physical mechanisms of the permeability stabilisation delay and match well with laboratory data. Long permeability stabilisation period during coreflood tests exhibiting fines migration is explained by slow fines rolling and sliding, and also by

the diffusive delay in particle mobilisation. The analytical models have been derived for both slow fines migration and delayed mobilisation. Laboratory coreflood tests to observe the effects of flow velocity and salinity on fines migration and consequent permeability decline have been carried out, with the measurements of breakthrough fines concentration and pressure drop along the whole core and its sections. Matching of the experimental data, along with the analysis of the tuned coefficients shows that the slow-particle model exhibits higher accuracy of matching and more typical strained-concentration dependency of the tuning parameters than the delay-release model. The effect of temperature on fines migration is analysed systematically, which can be applied to geothermal reservoir conditions.

In this thesis, a new analytical solution is derived for the simultaneous processes of deep bed filtration and cake build-up during injection of two-sized particles. Formation of low permeable external filter cake during drilling and water injection has been intensively studied in the literature. The external cake may significantly reduce the well index. There are no existing mathematical models accounting for simultaneous particle filtration through external cake and in the core. The proposed model in this work fills the gap. Two scenarios of cake formation are identified, corresponding to the high and low fractions of small particles injected, respectively. Laboratory coreflooding tests with injection of two-sized particles have been performed, from which the rate and pressure drop data are collected. The data treatment shows excellent agreement between the measured pressure drop history and the modelled result.

The derived mathematical models and their analytical solutions in this thesis are applicable to the prediction of the extent of formation damage and the well behaviour in different types of reservoirs, including oil/gas, geothermal and coal bed methane reservoirs. Also, these models can be applied to numerous environmental and chemical engineering processes, including the disposal of industrial wastes into aquifers, propagation of contaminants and pollutants in vadose zone, and industrial water treatment.

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. I give consent to this copy of my thesis when deposited in the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968. The author acknowledges that copyright of published works contained within this thesis resides with the copyright holder(s) of those works.

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Yulong Yang 15/07/2016

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Thesis by Publication

Published Journal Papers

Yang, Y., Siqueira, F. D., Vaz, A., You, Z. and Bedrikovetsky, P., 2016. Slow migration of detached fine particles over rock surface in porous media. Journal of Natural Gas Science and Engineering, 34: 1159-1173.

You, Z., **Yang, Y.**, Badalyan, A., Bedrikovetsky, P. and Hand, M., 2016. Mathematical modelling of fines migration in geothermal reservoirs. Geothermics, 59: 123-133.

Keshavarz, A., **Yang**, **Y.**, Badalyan, A., Johnson, R. and Bedrikovetsky, P., 2014. Laboratory-based mathematical modelling of graded proppant injection in CBM reservoirs. International Journal of Coal Geology, 136: 1-16.

Sacramento, R.N., **Yang, Y.**, You, Z., Waldmann, A., Martins, A.L., Vaz, A.S., Zitha, P.L. and Bedrikovetsky, P., 2015. Deep bed and cake filtration of two-size particle suspension in porous media. Journal of Petroleum Science and Engineering, 126: 201-210.

Oliveira, M. A., Vaz, A. S., Siqueira, F. D., **Yang, Y.**, You, Z. and Bedrikovetsky, P., 2014. Slow migration of mobilised fines during flow in reservoir rocks: Laboratory study. Journal of Petroleum Science and Engineering, 122, 534-541.

Submitted Book Chapter

Yang, Y., Siqueira, F. D., Vaz, A., Badalyan, A., You, Z., Zeinijahromi, A., Carageorgos T., Bedrikovetsky, P., 2016. Fines migration in aquifers and oilfields: laboratory and mathematical modelling, Springer.

International full-volume conference papers

Yang, Y., You, Z., Siqueira, F. D., Vaz, A., Bedrikovetsky, P., 2016. Modelling of slow fines migration and formation damage during rate alteration. SPE-182320-MS.

SPE Asia Pacific Oil & Gas Conference and Exhibition, 25-27 October, Perth, Australia.

Yang, Y., You, Z., Siqueira, F. D., Vaz, A., Bedrikovetsky, P., 2016. A New Phenomenon of Slow Fines Migration in Oil and Gas Fields (Laboratory and Mathematical Modelling). SPE-179027-MS. SPE International Conference and Exhibition on Formation Damage Control, 24-26 February, Lafayette, Louisiana, USA.

Bhattacharya, S. S., Paitaridis, J., Pedler, A., Badalyan, A., **Yang, Y.**, Carageorgos, T., Lemon, N., Bedrikovetsky, P., 2016. Fines Mobilisation by Low-Salinity Water Injection: 3-Point-Pressure Tests. SPE-178947-MS. SPE International Conference and Exhibition on Formation Damage Control, 24-26 February, Lafayette, Louisiana, USA.

A. Badalyan, Z. You, **Yang, Y.**, T. Carageorgos, U. Schacht, P. Bedrikovetsky, M. Hand, 2015. New Laboratory Method to Assess Formation Damage in Geothermal Wells. SPE-174199-MS. SPE European Formation Damage Conference held in Budapest, Hungary, 3–5 June.

Yang, Y., Sacramento, R. N., You, Z., Leibson, A., Waldmann, A. T. A., Zitha, P. L., Bedrikovetsky, P. G. 2014. External Cake Built of Bi-sized Particles in Well Injectivity and Drilling. SPE 169276. In SPE Latin America and Caribbean Petroleum Engineering Conference.

Siqueira, F. D., **Yang, Y.**, Vaz, A. S., You, Z., Bedrikovetsky, P. G., 2014. Prediction of Productivity Decline in Oil and Gas Wells Due to Fines Migration: Laboratory and Mathematical Modelling. SPE-171475-MS. SPE Asia Pacific Oil & Gas Conference and Exhibition, 14-16 October, Adelaide,

Z. You, A. Badalyan, **Yang, Y.**, P. Bedrikovetsky, M. Hand, C. Matthews, 2015. Modelling of productivity decline in geothermal reservoirs due to fines migration-induced formation damage. World Geothermal Congress, 19-25 April, Melbourne, Australia.