A novel technology for enhanced coal seam gas recovery by graded proppant injection

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DEDICATION

This thesis is deeply dedicated to:

My parents for all they have done in my life.

My wife for her love, understanding, support, encouragement, sacrifices and prayers offered to me throughout my study.

Contents

Abstract

Coal bed methane (CBM) is one of the world's fastest growing unconventional gas resources and offers the potential for much cleaner power than from traditional coal. However, low productivity index in coal bed methane reservoirs places them on the margin of economic efficiency. One of the key technological hurdles affecting the productivity index in CBM reservoirs is the extremely low permeability of coal's natural cleat and fracture system. Thus, development of new techniques for enhancing coal cleat permeability is essential for cost-effective gas production from CBM reservoirs.

The hydraulic fracturing is the most widely used CBM well stimulation method; however, the hydraulic fracturing is often restricted by the environmental regulations. Besides, the available injection power may not be sufficient to fracture the well. The way around this problem is stimulation of a natural cleat system keeping the reservoir pressure below the fracturing pressure.

The main objective of this study is to develop a new well stimulation technology utilizing graded proppant injection to allow sequential filling of both distant and near-well fractures. This mechanism leads to a significant enhancement of permeability and, therefore, improved well productivity. Mathematical modelling and experimental studies are conducted for stimulation of natural cleat system in coal bed methane reservoirs. The aim of this work is to determine an optimum injection schedule, i.e. the timely dependencies of the injected proppant size and concentration that avoids fracture closure during production stage and provides minimum hydraulic resistance in the system of fractures plugged by proppant particles.

The laboratory tests on one dimensional injection of different size particles into coal cores have been conducted under different effective stress conditions. Calculations of electrostatic interactions result in determining the physico-chemical conditions, favourable for particle-particle and particle-coal repulsion. The repulsion prevents: particle attachment to the coal surface, particle agglomeration and consequent formation damage due to external and internal cake formation. Particle placement with low-salinity water, which promotes the repulsion, improves the coal permeability.

A laboratory-based mathematical model is developed to describe the proppant-free water injection stage; capture kinetics of proppant particles in the natural fractures and calculation of an optimal injection schedule. The analytical model is derived for exponential stress-permeability relationship and accounting for permeability variation outside the stimulated zone. Field case studies show that the productivity index can be significantly increased by applying the stimulation technology developed in this thesis. The sensitivity analysis of well index shows that the most influential parameters are the stimulated zone size, injection pressure and the cleat system compressibility.

The above laboratory study, mathematical modelling and the field-scale predictions allow recommending the developed technology of graded proppant injection for improving gas recovery from Coal bed methane reservoirs.

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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Publications

Peer reviewed journal publications

1. **Keshavarz, A.,** Yang, Y., Badalyan, A., Johnson, R., Bedrikovetsky, P., 2014. Laboratory-based mathematical modelling of graded proppant injection in CBM reservoirs. *International Journal of Coal geology* 136, 1–16.
2. **Keshavarz, A.,** Badalyan, A., Carageorgos, T., Bedrikovetsky, P., Johnson, R., 2014. Stimulation of coal seam permeability by micro-sized graded proppant placement using selective fluid properties. *Fuel* 144, 228–236.
3. **Keshavarz, A.,** Badalyan, A., Carageorgos, T., Bedrikovetsky, P., Johnson, R., 2014. Enhancement of CBM well fracturing through stimulation of cleat permeability by ultra-fine particle injection. *Australian Petroleum Production and Exploration Association (APPEA) Journal* 54, 155-166.
4. **Keshavarz, A.,** Mobbs, K., Khanna, A., Bedrikovetsky, P., 2013. Stress-based mathematical model for graded proppant injection in coal bed methane reservoirs. *Australian Petroleum Production and Exploration Association (APPEA) Journal* 53, 337-346.
5. Khanna, A., **Keshavarz, A.,** Mobbs, K., Davis, M., Bedrikovetsky, P., 2013. Stimulation of the natural fracture system by graded proppant injection. *Journal of Petroleum Science and Engineering* 111, 71-77.
6. **Keshavarz, A.,** Badalyan, A., Bedrikovetsky, P., Johnson, R., Improving efficiency of hydraulic fracturing treatment in CBM reservoirs by stimulating the surrounding natural fracture system. *Australian Petroleum Production and Exploration Association (APPEA) Journal* (Accepted)

International conference papers and poster presentations

7. **Keshavarz, A.,** Khanna, A., Hughes, T., Boniciolli, M., Cooper, A., Bedrikovetsky, P. 2014. Mathematical model for stimulation of CBM reservoirs during graded proppant injection, presented at *SPE/EAGE Unconventional conference & Exhibition*, Vienna, Austria, 25-27 Feb, SPE 167758-MS.

8. **Keshavarz, A.,** Badalyan, A., Carageorgos, T., Bedrikovetsky, P., Johnson, R., 2014. Stimulation of unconventional naturally fractured reservoirs during graded proppant injection: experimental study and mathematical model, presented at *SPE/EAGE Unconventional conference & Exhibition*, Vienna, Austria, 25-27 Feb, SPE 167757-MS.

9. **Keshavarz, A.,** Badalyan, A., Carageorgos, T., Bedrikovetsky, P., Johnson, R., 2014. Enhancement of CBM well fracturing through stimulation of cleat permeability by ultra-fine particle injection, presented at *Australian Petroleum Production and Exploration Association (APPEA) Conference and Exhibition*, Perth, Australia, 6-9 April.

10. **Keshavarz, A.,** Mobbs, K., Khanna, A., Bedrikovetsky, P., 2013. Stress-based mathematical model for graded proppant injection in CBM reservoirs, presented at *Australian Petroleum Production and Exploration Association (APPEA) Conference and Exhibition*, Brisbane, Australia, 26-29 May.

11. Bedrikovetsky, P., **Keshavarz, A.,** Khanna, A., Mckenzie, M. M., Kotousov, A., 2012. Stimulation of Natural Cleats for Gas Production from Coal Beds by Graded Proppant Injection, presented at *SPE Asia Pacific Oil & Gas conference and exhibition*, Perth, Australia 22-24 Oct. SPE 158761-MS.

12. **Keshavarz, A.,** Badalyan, A., Bedrikovetsky, P., Johnson, R., 2015. Improving efficiency of hydraulic fracturing treatment in CBM reservoirs by stimulating the surrounding natural fracture system, accepted for presentation at *Australian Petroleum Production and Exploration Association (APPEA) Conference and Exhibition*, Melbourne, Australia, 17-20 May.

13. **Keshavarz, A.,** Badalyan, A., Bedrikovetsky, P., Johnson, R., 2015. Graded Proppant Injection into Coal Seam Gas and Shale Gas Reservoirs for Well Stimulation, accepted for presentation at *SPE European Formation Damage Conference & Exhibition*, Budapest, Hungary, 3-5 June, SPE-174200-MS.

14. **Keshavarz, A.,** Badalyan, A., Bedrikovetsky, P., Johnson, R., 2015. A new technique for enhancing hydraulic fracturing treatment in unconventional reservoirs: experimental study and mathematical modelling, accepted for presentation *at SPE EUROPEC Conference & Exhibition*, Madrid, Spain, 1-4 June, SPE-174354-MS.