Fuel 144 (2015) 228–236

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Stimulation of coal seam permeability by micro-sized graded proppant placement using selective fluid properties

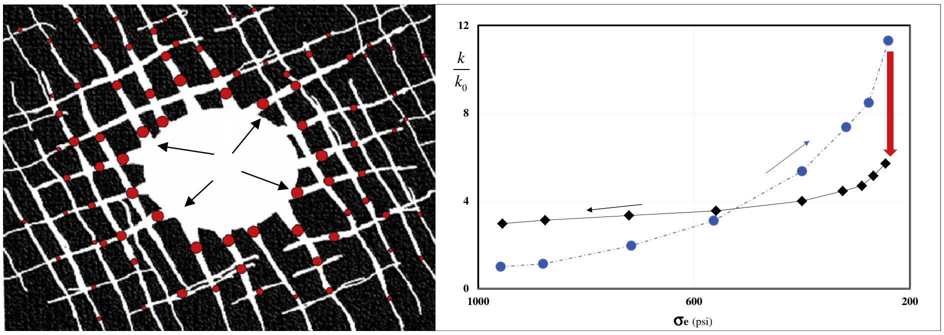
Alireza Keshavarz, Alexander Badalyan, Themis Carageorgos, Pavel Bedrikovetsky *, Raymond Johnson Jr.

Australian School of Petroleum, The University of Adelaide, Adelaide, Australia

HIGHLIGHTS

- Repulsion between particles and coal is a favourable condition for graded proppant injection.
- No permeability increase is observed after high salinity water injection with proppant.
- High efficiency of graded particle injection using low salinity water is observed.
- Graded proppant placement yields threefold increase in coal core permeability.
- Graded proppant injection results in six-times well productivity increase.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 20 June 2014
Received in revised form 15 December 2014
Accepted 15 December 2014
Available online 26 December 2014

Keywords:
Coal bed methane
Permeability
Stimulation
Cleats
Proppant injection
Ionic strength

ABSTRACT

During initial drawdown in coal bed methane (CBM) production, the coal permeability declines due to partial fracture closure. The recently proposed technique for stimulation of natural coal fractures and cleats by the graded proppant injection targets a uniform cleat filling by the proppant. It provides maximum opening and conductivity during pressure depletion. The technique for graded particle injection below the fracturing pressure has been experimentally evaluated using injection of micro-sized ultra-light high-strength particles into coal cores. The laboratory tests on one-dimensional injection of different size particles into coal cores have been conducted under different effective stress conditions. Calculation of electrostatic interactions results in determining physico-chemical conditions that are favourable for particle–particle and particle–coal repulsion. The repulsion condition prevents particle attachment to the coal surface, particle agglomeration and also formation damage due to external and internal cake formation on the fractures' surface. Particle placement in repulsion condition with low-salinity water results in almost three-time increase in coal permeability. Implementation of an empirical permeability shape factor allows matching the laboratory data by the mathematical model. The laboratory-based mathematical modelling as performed for the field conditions shows that the proposed method can yield up to six-time increase in productivity index.

1. Introduction

Coal bed methane (CBM) reservoirs are characterised by extremely low well productivity due to low aperture, and low density of

---

* Corresponding author. Tel.: +61 883133082.
E-mail address: pavel.bedrikovetsly@adelaide.edu.au (P. Bedrikovetsky).

http://dx.doi.org/10.1016/j.fuel.2014.12.054

Nomenclature

a	cleat spacing, L
C_f	cleat compressibility, $\mathrm{M^{-1}\,LT^{2}}$
D	core diameter, L
E	Young's modulus of elasticity, $\mathrm{M\,L^{-1}\,T^{-2}}$
f	permeability correction factor
h	cleat aperture, L
h^*	separation distance, L
I	ionic strength
k	permeability, $\mathrm{L^{2}}$
l	distance between adjacent proppant particles, L
L	core length, L
p	pore pressure, $\mathrm{M\,L^{-1}\,T^{-2}}$
p_f	fracturing pressure, $\mathrm{M\,L^{-1}\,T^{-2}}$
p_{res}	reservoir fluid pressure, $\mathrm{M\,L^{-1}\,T^{-2}}$
p_w	fluid pressure at wellbore, $\mathrm{M\,L^{-1}\,T^{-2}}$
p_{inlet}	inlet pressure, $\mathrm{M\,L^{-1}\,T^{-2}}$
p_{inj}	injection pressure, $\mathrm{M\,L^{-1}\,T^{-2}}$
PI_o	well productivity index of non-stimulated reservoir, $\mathrm{M^{-1}\,L^{2}\,T^{3}}$
PI	well productivity index of stimulated reservoir, $\mathrm{M\,L^{-1}\,T^{-2}}$
r_e	drainage radius, L
r_s	particle radius, L
r_{st}	stimulation radius, L
S	permeability shape factor
V_{tot}	total potential of interaction, $\mathrm{M\,L^{2}\,T^{-2}}$

Greek letters

α	biot effective stress coefficient
β	dimensionless packing aspect ratio
ε_σ	dimensionless stress
ν	Poisson's ratio
σ	stress, $\mathrm{M\,L^{-1}\,T^{-2}}$
σ_e	effective stress, $\mathrm{M\,L^{-1}\,T^{-2}}$
σ_h	minimum horizontal stress, $\mathrm{M\,L^{-1}\,T^{-2}}$
σ_H	maximum horizontal stress, $\mathrm{M\,L^{-1}\,T^{-2}}$
ϕ_c	cleat porosity

Subscript

o	initial value of a parameter
exp	experiment
model	model

Abbreviations

CBM	coalbed methane
DLVO	Derjaguin–Landau–Verwey–Overbeek
CFD	computational fluid dynamics

natural fractures and cleats. Hence, the main challenge for cost effective production is an increase of well productivity [1].

Hydraulic fracturing is the main well stimulation technique applied in CBM wells [2,3]. However, environmental and reservoir sealing restrictions together with a lack of injectivity power often prevent the use of hydraulic fracturing for well stimulation.

Rahman et al. [4] proposed a shear dilation stimulation technique in which permeability of natural fracture systems increases during fluid injection below fracturing pressure to improve permeability of natural fracture systems. However, after injected fluid is produced, the open fractures tend to close back. As a result of fracture closure, shear dilation of natural fracture system remains the sole reason for improved permeability.

Graded proppant particle injection into natural fracture system was recently proposed as a new alternative method for stimulation of CBM wells [5]. The fracture width and pore pressure decrease with radius during injection into CBM wells. Sequential injection of proppant particles with decreasing concentration and increasing size leads to a uniform filling of the fractures. It prevents fracture closure after injection and keeps the fractures open during water and gas production. As the result, the final permeability after proppant placement is higher than the initial coal bed permeability. The mathematical modelling confirms significant well productivity increase after stimulation by graded proppant injection; however, neither the model nor the proposed method has been validated experimentally.

The efficiency of the graded particle injection depends on whether the rock conductivity is provided by the fractures or pores (Fig. 1). The abscissa axis is directed according to pore pressure increase that corresponds to the decrease of effective stress. According to Fig. 1, the permeability increases due to the increase of the pore pressure during water injection (black curve). The red[1] arrow in Fig. 1 corresponds to permeability decline after the proppant placement due to increased hydraulic resistance. The permeability decreases with decrease of the pore pressure (shown by the green and blue curves in Fig. 1). In clastic reservoirs with pore-dominated hydraulic conductivity, the graded particle injection causes pore plugging by the particle straining with the consequent permeability reduction (see blue line and core cross-section with blue particles); the final permeability is lower than the initial permeability. While, the method can result in permeability increase in rocks with fracture-dominated transport mechanism (e.g., coals, shales and carbonates), where the residual fracture opening after particle placement prevents fracture closure after the effective stress increase (see green line and core cross-section with green particles in Fig. 1). In the case of coals, the meso- and micro-porosities are low and discontinuous with initial production dominated by natural fractures and cleats [6]. Permeability of the coal beds is dominated by the cleat conductivity and is strongly dependent on effective stress (see the corresponding examples in [7]). This makes coal bed reservoirs good candidates for stimulation by the graded proppant injection.

Apart from the "fracture/pore" domination criterion, there are other parameters that affect the efficiency of the graded proppant injection method. Inadequately defined particle sizes and concentrations may yield the conductive fractures blockage without achieving the desired invasion depth [8]. The particle–coal attraction, determined by ionic strength and pH of the carrier fluid can cause formation of an external filter cake on the injection face [9,10]. A current comprehensive review of the literature reveals that, the effects of the proppant size and the carrier fluid chemistry on the return permeability of the stimulated natural coal cleat and fracture systems have not been investigated.

The laboratory tests show that the injection of water with chemical composition that provides the particle–particle and particle-rock repulsion results in significant permeability enhancements. The proper carrier–water composition has been determined from the DLVO theory for electrostatic interaction. The mathematical model has been modified by introduction of empirical shape factor for the model tuning. The modelling-based

---

[1] For interpretation of color in Figs. 1, 4, 7–9 the reader is referred to the web version of this article.