Chemical Engineering Science 149 (2016) 63–77

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Multiphase reactive-transport simulations for estimation and robust optimization of the field scale production of microbially enhanced coalbed methane

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HIGHLIGHTS

- A reactive-transport model for biogenic coalbed methane generation is developed.
- Proxy models are developed using polynomial chaos expansion.
- Optimal strategies are devised for nutrient injection and bottomhole pressures.
- Trade-offs between nominal performance and robustness are explored.

ARTICLE INFO

Article history:
Received 10 November 2015
Received in revised form
28 March 2016
Accepted 8 April 2016
Available online 9 April 2016

Keywords:
Coalbed methane (CBM)
Reservoir simulation
Polynomial chaos expansion
Robust optimization

ABSTRACT

The discovery that approximately 20% of natural gas is microbial in origin has elevated interest in microbially enhanced coalbed methane (MECoM). However, a rational approach to exploit this calls for the development of reservoir scale models that include the effect of microbial activity. To address this, we have developed a multiscale, multiphase, multicomponent reactive-transport model for the production of microbially enhanced coalbed methane (MECoM) that includes microbial kinetics. The model is used to evaluate field scale strategies for commercial MECoM production. Optimization studies are also conducted over a range of compositions of the injected nutrient and injector bottomhole pressures. In order to account for the effect of uncertainty in the model parameters, mean-variance robust optimization is performed, allowing a trade-off between performance and robustness. Proxy modeling is performed in a multivariate polynomial chaos expansion framework to evaluate the cost functions involved in the robust optimization and sparse expansions are constructed in order to deal with issues related to high dimensionality. The optimization strategy is tested for different trade-offs between robustness and performance. It is observed that for the given case, the location of robust optimal points does not vary unless only robustness is included in the objective function, and nominal performance is not.

1. Introduction

Coalbed methane, the gases trapped in coalbeds, are a mixture of methane (80–90% by volume) and minor amounts of carbon dioxide, nitrogen, hydrogen sulfide, sulfur dioxide and heavier hydrocarbons such as ethane, propane and butane. Following rapid technology developments, the high fuel efficiency of CBM coupled with low GHG/toxic gas emissions and zero waste disposal have positioned CBM as a significant source of natural gas. In 2008, the International Energy Agency reported that CBM contributed to 10%, 4% and 8% of natural gas production in the United States, Canada and Australia, respectively. India, China, Russia and Indonesia are also investing in CBM extraction on large scales (Stevens, 2010; Senthamaraikkannan et al., 2015). However, there are many key issues impeding the development of commercial scale CBM production. Among these, the low productivity of gas wells and the ensuing high investment requirement in drilling multiple wells are big challenges, apart from the issues of heterogeneity of coal beds, economics of gas demand and supply, water and environmental management, the availability of gas and water pipelines, etc. (Stiller et al., 2014).

There are two dominant processes by which CBM is produced – thermal cracking at elevated temperatures and pressures, and

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http://dx.doi.org/10.1016/j.ces.2016.04.017
0009-2509/

anaerobic microbial attack of organic matter. When thermal processes begin to dominate during coal formation, microbial activity is usually suppressed. However, recent laboratory and field experiments have indicated that in addition to microbial CBM generated in the past, many basins have active ongoing biogenic methane generation (Ritter et al., 2015; Martini et al., 1998; Ulrich and Bower, 2008). Restoration of microbial activity in these basins is considered to be the result of triggering events such as basin uplift and cooling, the flow of underground water, and the dilution of salinity levels (Ulrich and Bower, 2008; Parkes et al., 2000). The microbial CBM produced after these events is referred to as secondary biogenic methane. It is estimated that approximately 20% of the methane produced worldwide is microbial in origin (Rice and Claypool, 1981). Microbially enhanced coal bed methane production (MECoM) seeks to enhance the production of secondary biogenic methane through improved productivity of existing gas wells along with the bioconversion of deep, unmineable coal into fuels.

1.1. Microbially enhanced coalbed methane

The four primary strategies employed for MECoM are microbial stimulation by addition of nutrients, microbial augmentation by addition of microbes, physically increasing fracture spacing to provide more access to microbes and nutrient amendments, and chemically increasing the bioavailability of coal organics (Ritter et al., 2015). Many laboratory studies have been conducted to evaluate each of these effects. Laboratory incubation studies on lignite and sub-bituminous coals by Harris et al. (2008) showed that substantial methane production occurs in the presence of H_2/CO_2 and inorganic nutrient amendments. Studies by Singh et al. (2012) on an Indian coal bed sample showed that methane production in the presence of formation waters and native microbial population improved considerably with the addition of nitrite. Experiments by Opara et al. (2012) on lignite, bitminous coal and coal wastes with selected microbial inocula and different types and levels of nutrient amendments showed that methane production increased with increasing nutrient concentrations. The addition of organic nutrients such as tryptone and Brain Heart Infusion (BHI) was shown to improve methane production in subbituminous coal samples from western Canada by Penner et al. (2010). Jones et al. (2010) observed that bioaugmentation with a consortium of bacteria and methanogens enriched from wetland sediment accompanied by biostimulation with nutrient amendments generated methane more rapidly and to a higher concentration as compared to biostimulation without the amendments. Experiments by Papendick et al. (2011) on native Walloon coal with produced waters from the Surat basin showed that the initial methane production rate and the final methane yield increased by 240% and 180%, respectively, on the addition of a Zonyl FSN surfactant to improve coal bioavailability. Similarly, Huang et al. (2013) showed that methane production increased when coal samples were treated with potassium permanganate, a depolymerization agent that aids in coal solubilization.

Many field scale studies have also been carried out on biogenic methane production. Successful pilot scale field tests for microbial stimulation of CBM production were conducted by Luca Technologies, Inc. to restore gas production in existing wells in the Powder River Basin, Wyoming. Similarly, Crisis Energy and Next Fuel, Inc. have also conducted smaller field scale tests. Also, Archtech, Synthetic Genomics and ExxonMobil hold patents related to MECoM (Ritter et al., 2015). US patent 7696132 (Pfeiffer et al., 2010) describes methods for stimulating biogenic production with enhanced hydrogen content using a combination of hydrogen and phosphorous compounds, US patent 5424195 (Volkwein, 1995) describes a method using household sewage injection into an abandoned coal mine to provide feedstock for the bacteria, US patent 20040033557 (Scott and Guyer, 2004) describes a method for the injection of bacteria and nutrients under pressure into naturally occurring fractures or cleats as well as fractures induced during the stimulation of coalbed methane gas wells, US patent 20140034297 (Mahaffey et al., 2014) describes methods for dispersion of nutrient amendments and US 7640978 (Pfeiffer et al., 2010) describes methods for contacting subsurface coalbeds with microbes under anaerobic conditions to form a reaction mixture.

Although numerous studies have been carried out, a key link in the commercialization of any such technology is the capacity to conduct model-based analysis for technology transfer over increasing scales along with process estimation, optimization and control at field scales. For instance, Luca's operational approach was batch treatment of wells with nutrient amendments, followed by the assessment of new gas formation after many months or years, whereas Ciris adopted a continuous-flow injection process using 4 injection wells surrounded by 13 production wells, recirculating 1000–2000 barrels of water every day. Since there is no rigorous approach for the appraisal of these operating procedures, optimum injection procedures cannot be resolved and process efficiency is likely to be compromised. Thus, if suitable modeling and simulation tools are not used, decisions related to production forecasting, well completions, etc. are likely to be sub-optimal. In this work, we attempt to address this issue by using suitable reservoir scale models simulated in CMG STARS (Computer Modeling Group, 2011), which are then used in process optimization.

1.2. Reservoir simulation of field scale coalbed methane production

In our previous study (Senthamaraikkannan et al., 2016), we developed a gas phase transport model for dual porosity coalbed reservoirs and coupled it with a kinetic model based on the assumption that microbes survive only on residual pore water. However, this is not directly applicable in the assessment of commercial field applications where formation and injection waters are present in excess. Moreover, since studies have indicated that native microorganisms found in coal formations are usually nutrient-limited (Penner et al., 2010), it is also necessary to include nitrogen limitations in the kinetic model. Taking these issues into account (based on the kinetic model for multi-substrate limited case in our previous study, Senthamaraikkannan et al., 2016) and coupling the kinetic model with field scale transport, we develop reservoir models for simulations in the Advanced Process and Thermal Reservoir Simulator 2011.10 (STARS) (Computer Modeling Group, 2011) by the Computer Modeling Group (CMG). The predicted gas production from the simulations is subsequently employed in field scale process optimization.

As described in our previous study (Senthamaraikkannan et al., 2016), multi-porosity coalbeds can be characterized satisfactorily by dual porosity, with the primary and secondary porosity being referred to interchangeably as macropores and micropores or fractures and matrix, respectively. Primary porosity consists of fractures or macropores $(> 50\ \text{nm})$ and mesopores of dimensions 2–50 nm, while secondary porosity consists of micropores of dimension <2 nm (Wei et al., 2007; Shi and Durucan, 2003; Ryu et al., 1999). Gas transport in this dual scale porous system is modeled by a dual step transport mechanism consisting of Darcy's flow in macropores and diffusive flow in the micropores. Micropore gas diffusion is controlled by surface desorption and diffusion through the coal matrix, both of which are lumped based on a pseudo steady-state approach to treat diffusion as a one-step process. This method models matrix response relative to pseudo steady-state adsorbed gas concentrations in a lumped parameter