Journal of Natural Gas Science and Engineering 33 (2016) 942–953

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

Optimisation of gas mixture injection for enhanced coalbed methane recovery using a parallel genetic algorithm

Mohammad Sayyafzadeh [a], Alireza Keshavarz [b, *]

[a] The University of Adelaide, Australian School of Petroleum, Australia
[b] CSIRO, Energy Business Unit, Australia

A R T I C L E I N F O

Article history:
Received 14 February 2016
Received in revised form
25 May 2016
Accepted 13 June 2016
Available online 15 June 2016

Keywords:
ECBM
Varying composition injection
Optimisation
CO2-sequestration
Genetic algorithm
Coalbed

A B S T R A C T

Gas injection in coalbed Methane reservoirs is an environmentally friendly and economically viable enhanced recovery technique. Promising results can be obtained by injecting a mixture of CO2 and N2. The optimum composition is a function of geomechanical and sorption characteristics of the coal.

In the current study, it is sought to optimise the composition of the injected gas, based on an economic objective function. The decision variables are the composition of the injected gas and the injection rate that can be both subjected to change over a continuous injection. In the formulated objective function, the OPEX costs (e.g., separation, compression for injection and injectant supply) and the income, resulting from, CH4 production and CO2 sequestration are considered. This optimisation problem is nonlinear, and the corresponding search space is high-dimensional. Therefore, a sophisticated optimisation algorithm is required. For this study, a parallel real-value genetic algorithm is coded in MatLab and coupled to a commercial coalbed simulator (ECLIPSE-E300). This interface allows us to measure the goodness of each solution-candidate and also to perform optimisation automatically.

The algorithm is used to optimise rates and compositions of a semi-synthetic ECBM case study, and the optimum scenario is compared with the optimum scenario of a constant composition injection. The comparison confirms that a varying-composition strategy results in more revenue from an ECBM project. In this study, also, the optimum solution for different economic conditions are approximated and then the optimum solutions are compared with each other to investigate the effect of carbon credit and Methane price on the injection schedule.

In those economic conditions that carbon credit is higher than CO2 supply costs, the optimum scenarios tend to yield a higher amount of sequestrated CO2, and in all of them, the optimum schedules are the ones that start with a very low fraction of CO2 in the injected gas and continue by a gradual increase of CO2 fraction. In other economic conditions, the optimum scenarios move towards the ones that less CO2 is injected.

1. Introduction

Coalbed Methane (CBM) reservoirs are naturally fractured rocks, consisting of cleats and matrix (Gray, 1987; Gamson et al., 1996; Palmer, 2010; Seidle, 2011; Keshavarz et al., 2014, 2015). The micropores of coal matrix are the major sites for the storage and can hold a considerable amount of gas in the adsorbed phase on the walls of the pores (Gamson et al., 1996; Gilman and Beckie, 2000; Xu et al., 2013a,b; Verma and Sirvaiya, 2016). This storage characteristic distinguishes CBM from the conventional reservoirs in which gas is trapped mostly in the free state (Seidle, 2011). Coal matrixes are typically enclosed by a cleat system and the bedding planes, and do not contribute directly into the flow to the wellbore (Seidle, 2011; Palmer, 2010; Clarkson et al., 2010). Gas can only flow to the neighbouring cleats, via diffusion (Staib et al., 2015a,b). In contrast with the matrix, cleats are well-connected through two sets of perpendicular fractures, face and butt cleats (Paul and Chatterjee, 2011a,b), which create a decent connection between the wellbore and the reservoir (Clarkson et al., 2010). The cleats are usually filled with water at the initial condition, and this creates the sufficient pressure (usually equal to hydrostatic pressure) to avoid the discharge of gas from the matrix.

* Corresponding author. CSIRO, Energy Business Unit, 11 Julius Ave, North Ryde, NSW, 2113, Australia.
E-mail address: alireza.keshavarz@csiro.au (A. Keshavarz).

http://dx.doi.org/10.1016/j.jngse.2016.06.032
1875-5100/

At the primary stages of production, (known as dewatering), only water is produced, and meanwhile the reservoir pressure declines. This pressure drawdown leads to the liberation of gas from the matrix, once the reservoir pressure falls below the equilibrium pressure corresponding to the gas content. The desorbed gas diffuses from the matrix to the cleats, and then flows, along with the remaining water, from the cleats to the wellbore (Seidle, 2011). The gas rate increases, by the reduction of water-in-place, and the two-phase flow continues until the water saturation falls below the residual saturation (Seidle, 2011). After that, there will be a single-phase flow of gas, until the reservoir pressure reaches the abandonment pressure. This process is known as the natural depletion and is not expected to result in more than 50% gas recovery (Puri and Yee, 1990). To enhance the recovery and improve the production rate, the reservoir pressure should be maintained and simultaneously the Methane partial pressure gradient, between cleats and matrix, increases. This can be obtained by a continuous injection of a foreign gas into the coal, known as enhanced coalbed Methane (ECBM). The injected gas sweeps Methane in the cleats, resulting in Methane partial pressure drop (which accelerates desorption), while maintains the reservoir pressure, keeping the cleats open.

Several laboratory, simulation, pilot and field studies have shown that CO2 (Carbon Dioxide) injection can increase Methane recovery (Fulton et al., 1980; Sinayuç and Gümrah, 2009; Stevens et al., 1998), and has carbon sequestration benefits (Wong et al., 2000). In such a technique, there is a major problem, cleats closure due to matrix swelling (Durucan and Shi, 2009; Durucan et al., 2009). Mazzotti et al. (2009) measured the changes of cleats volume, by exposing coal samples to different gases (CO2, N2, CH4 and He), the results indicated that the coal is swollen more severely by CO2 in comparison with the others, which is because of greater affinity of coal towards CO2 (Fulton et al., 1980; Moore, 2012; Fang et al., 2013). As a result of this fact, the well injectivity might lessen by two orders of magnitude (Durucan and Shi, 2009). Another set of studies have shown that a rapid production rate enhancement can be achieved by N2 (Nitrogen) injection (Reeves and Oudinot, 2004; Perera et al., 2015). However, an early N2 breakthrough was observed, which degrades the quality of the produced gas (Reeves and Oudinot, 2004; Zhou et al., 2013a). The quick increment of production rate is due to the improvement of well injectivity (Shi et al., 2008).

Shi and Durucan (2005) conducted a micro-pilot study in the Fenn Big Valley to analyse the effect of CO2/N2 mixture on ECBM performance, and the investigations indicated that flue gas (a mixture of N2 and CO2) injection results in a better performance, compared to pure N2 and CO2. Durucan and Shi (2009) also carried out a simulation analysis on a similar subject, and it was concluded that injecting a mixture of 13% CO2/87% N2 through a continuous injection would result in the highest Methane recovery, while the quality of produced gas is not degraded significantly and well injectivity does not decline sharply. In a recent study (Sayyafzadeh et al., 2015), it has been shown that the performance (recovery and also production rate) of mixture gas injection can be improved by applying a varying composition strategy, throughout a continuous injection of N2/CO2 mixture. A series of sensitivity analyses were performed to find an optimal scenario. The results of the optimum scenario then were compared with the outcomes of the optimum scenario of fixed composition gas injection. The criterion of comparison was the ultimate Methane recovery, and therefore, by executing a few scenarios, an optimum for each strategy could be approximated.

To have a better criterion for the comparison, in this study, an economic objective function (net-present-value) is defined to measure the goodness of the ECBM scenarios (fixed composition injection and varying composition injection). In the objective function, the following terms are taken into consideration: ultimate Methane recovery, ultimate Carbon sequestration, compression costs, separation costs, injectant supply costs and a discount rate which takes into account the effect of production/injection rates. Because of the number of elements impacting the fitness value of the scenarios and due to the nonlinearity of the function, the optimum scenario cannot be found with a simple sensitivity analysis. Hence, an optimisation algorithm is implemented. For this study, a real-value parallel genetic algorithm is coded in MatLab (Matlab, 2013a) and coupled to a commercial coalbed simulator (ECLIPSE-E300) (Schlumberger, 2013), to find the optimum scenario, for a semi-synthetic case study. Genetic algorithm has a long history in oil and gas industry and thus far, different forms of genetic algorithm have been used in research studies (Sayyafzadeh et al., 2012, Salmachi et al., 2013; Sayyafzadeh, 2015b; Romero and Carter, 2001; Velez-Langs, 2005). In the current study, the effect of gas price and carbon sequestration credit on the optimum point (the best injection schedule) is also investigated.

In the next section, decision variables, modelling, objective function formulation and optimisation are explained. Model description section presents the details of coal and gas characteristics used for building the simulation-model. In the results and discussion section, the outcomes of the proposed method are presented and analysed. In the last section, some conclusive remarks are given.

2. Methodology

In order to find an economically optimal gas injection scenario for an ECBM project, the following steps should be done: i-defining the decision variables and the feasible region of the corresponding search space, ii-integrating a numerical simulation into a programming language, in order to deliver forecasts for each scenario and extract the required data from the simulation output, automatically, iii-formulating an objective (fitness) function to quantitatively distinguish among the scenarios (solution-candidate), based on the extracted data and iv-designing an optimisation algorithm to search the solution space, for the best scenario (i.e., to approximate the global optimum point of the formulated function). For this study, a real-valued genetic algorithm (GA), as a common evolutionary optimisation algorithm, is coded and utilised. These steps are explained, in details, in the following subsections.

2.1. Defining the decision variable

In the current work, it is sought to investigate which strategy results in more revenue from an ECBM project, varying the composition of injectant, through a few practically feasible steps (n_t), or a constant composition injection. To answer this question, n_t decision variables per injector should be defined (as the alterations are step-wise) to represent the percentage of CO2 in the N2/CO2 mixture injection in each step. The minimum and maximum of these variables are zero and one, respectively. In addition to the injectant composition, the injection rate in each of these steps, through controlling well bottomhole pressure, are considered as decision variables, in order to increase injection flexibility. The range of possible values for this set of variables is from the hydrostatic head (i.e., no flow) to a pressure lower than fracing pressure (p_f). The decision variables are summarised in Table 1, for a reservoir with a pair of wells. The corresponding search space is a bounded $2n_t$ dimensional continuous space, and X is a point in this space.