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Efficient optimization framework for integrated placement of horizontal wells and hydraulic fracture stages in unconventional gas reservoirs

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ABSTRACT

Rapid advances in horizontal well drilling and hydraulic fracturing have made these technologies standard development strategies in unconventional gas reservoirs. Further improvements in these practices by means of numerical optimization of wellbore locations and hydraulic fracture (HF) stages spacing can enhance shale gas reserves and increase revenue from the unconventional projects. In order to solve these two challenges simultaneously as an integrated optimization problem, an automated framework for placement of horizontal wellbores and HF stages is developed and tested in this paper. Coupled with expert knowledge and engineering judgment, this workflow allows to produce unconventional assets economically.

This paper presents specifics of our novel optimization framework that improves the design and placement of HF stages in shale gas reservoirs and increases production and the net present value (NPV) of the projects by judicious application of numerical optimization algorithms. In particular, we test several gradient-based and gradient-free methods, namely, simultaneous perturbation stochastic approximation (SPSA), Genetic Algorithm (GA), and covariance matrix adaptation evolution strategy (CMA-ES). Application of these optimization strategies to a suite of test cases illustrates that it is not necessary to assume even spacing between HF stages because the algorithms have a capability to optimize HF stages spacing in homogeneous and heterogeneous geologic systems.

1. Introduction

Unconventional resources, such as tight gas sands and shale gas reservoirs, are reshaping the energy supply structure in the United States and are being established as the main cleaner energy sources in the twenty first century (Curtis, 2002; Jenkins and Boyer, 2008). Economic production of natural gas from shale formations requires favorable petrophysical properties and good well completion potential. Successful completion design depends heavily on a given well location. Therefore, optimal choice of well placement location as well as the number and spacing of hydraulic fractures (HF) stages is critical for meeting commercial production goals.

Hydraulic fracturing operations in gas-rich shale reservoirs tend to be complex and capital consuming (Holditch, 2007). This new technique has been changing the energy future worldwide (Energy Information Administration, 2010). In order to bring the costs down and facilitate the best development practices, reservoir and production engineers might want to utilize an automated approach to wellbore and HF stages placement that can effectively search the wide domain of the objective function for the optimal solution. Benefits of the automated framework are hard to overestimate. Although better petrophysical characterization of shale formations and the engineers' judgment can reduce the search space significantly, optimization algorithms are still the most rigorous strategies for obtaining specific values for desired control variables in a systematic fashion (Cipolla, 2009). There are several optimization works that designed evenly or uniform HF spacing frameworks in shale gas reservoir with given fixed HF locations (Holt, 2011; Yu and Sepehrnoori, 2013). We propose the numerical optimization workflow that can be used in combination with the expert knowledge to enhance gas reserves and increase revenues from shale gas projects.

Below we formulate the optimization problem of horizontal well placement and spacing of HF stages mathematically, and introduce the details of the proposed framework. The framework is a hierarchical optimization problem with two levels. On the upper level our workflow searches for the best wellbore location or locations (in case of more than one well). Once such location

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Nomenclature

A	SPSA non-negative coefficient	H_j	Number of HF stages in well j
a_k	SPSA non-negative coefficient	C_f	HF cost per stage, $
b	Discount rate, %/100/year	C_p	Penetration cost of per drilled gridblock
C	Covariance matrix C in CMA-ES	N_{prod}	Production well index
c	SPSA non-negative coefficient	u	Control variable vector
c_k	SPSA gain sequence	P	Pressure, psi
K	Total number of steps in simulation	P_L	Langmuir pressure parameter, psi
g	Gradient of the objective function J	V	Adsorbed gas content, *Mscf/ton*
λ	Population size of offspring number in CMA-ES	V_L	Langmuir volume parameter, *Mscf/ton*
$Q_{g,j}^k$	Gas production rate, Mscf/day	α	SPSA non-negative coefficient
Q_j	Operating cost of well j, $/day	γ	SPSA non-negative coefficient
r_g	Gas price, $/Mscf	Δ_k	SPSA perturbation parameter
t^k	Year period, days	σ	Coordinate wise standard deviation (step size) in CMA-ES
C_w	Base cost for drilling a horizontal well, $		

is calculated, it is fixed and passed to the lower level of the workflow. On this level one of the chosen algorithms computes the optimal number, locations and spacing of HF stages by varying the control vector and evaluating the net present value (NPV) objective function.

To solve the discrete optimization problem described above, we employ and compare several algorithms: Simultaneous perturbation stochastic approximation (SPSA), Genetic Algorithm (GA), and covariance matrix adaptation evolution strategy (CMA-ES). All three algorithms are implemented and used to investigate the discrete hierarchical problem of wellbore and HF stages placement. Results of the synthetic test runs reveal advantages and shortcomings of each algorithm and demonstrate clear benefits of our systematic approach to shale gas development.

2. Background and methodology

This section discusses most general mathematical statement of our optimization problem and defines specifics applicable to HF and well placement optimization. The long-term objective function is described with key economic parameters and production variables. The section ends with rigorous introduction to the three optimization algorithms that lie in the heart of our framework.

2.1 Objective function

To define the optimization problem of wellbore and HF placement, we first formulate the objective function J that allows comparing results of all test cases on a common basis. One of the most popular objective functions in oil and gas industry is NPV. In a general mathematical framework, the optimization problem can be stated as follows: find the optimal locations of HF stages u such that

$$u^* = arg\max_{u\in U} J(u), \tag{1}$$

where $J(u)$ is the NPV objective function with key economic parameters. The search space for the optimal solution u^* is the number and locations of possible HF stages. In our numerical simulation framework u is also labeled as a control vector of integer numbers.

The NPV function is a complex mathematical expression that describes long-term project objectives. It contains terms accounting for the cost of each HF stage and the number of HF stages. In addition, the objective function J includes gas production and water disposal rates as well as drilling and operational costs. All production scenarios are tested on the twenty years production period with some reasonable approximation of the discount rate. The NPV function that optimizes locations and number of HF stages of equal half-lengths as well as well locations has the following form:

$$J = \sum_{k=1}^{K}\left[\sum_{j=1}^{N_{prod}} \frac{\left(Q_{g,j}^k \cdot r_g - r_w - Q_j\right)\cdot \Delta t^k}{(1+b)^{t^k/365}}\right] - \sum_{j=1}^{N_{prod}}(C_w \cdot j + H_j C_f + H_j C_p) \tag{2}$$

In this expression, the first summation term stands for the discounted revenue from the well operations and the second term accounts for drilling and fracturing costs (Holt, 2011). Each parameter of the function J is defined as follows: K is the total number of simulation time steps, k is the time index, Δt^k [year] is the length of time period, and b is the discount rate [%/100/year]. N_{prod} is the number of production wells, $Q_{g,j}^k$ is gas production rate for a producer j [Mscf/day] at year k, and r_g is constant gas price [$/Mscf]. In order to describe project's operational and capital expenses, we use Q_j [$/day] as the operating cost of the well j, C_w [$] as the base cost of drilling a horizontal well, C_f [$] as the hydraulic fracturing cost per stage, H_j as the number of HF stages along the well j, and, finally, C_p [$] as the drilling penetration cost of a gridblock. Table 1 provides specific values for the main parameters of the objective function J.

2.2 Workflow for production design optimization

Now that we defined the objective function J for our discrete optimization problem, we propose the optimization workflow that in combination with the expert knowledge can enhance gas reserves and increase revenues from shale gas development. Most proposed solutions for the HFs placement problem simply assume all HF stages are spaced with uniform distance between each other. We develop the optimization workflow that allows for non-even HF stages spacing, because our optimization algorithms remove this constraint and automatically selects both the number and locations of the stages. Before we present the key findings and

Table 1
Parameter values for the NPV function. (Schweitzer and Bilgesu, 2009; Bruner and Smosna, 2011).

Property	Unit	Value
Gas price (at the wellhead)	$/ft^3	3.2
Cost of water disposal	$/bbl	1.0
Discount rate	%/100	13
Base cost for drilling per well	$	2.00E + 06
Penetration cost per gridblock	$	6.00E + 03
Fracturing cost per HF stage	$	1.30E + 05
Operating cost per well	$/day	60