Journal of Unconventional Oil and Gas Resources 15 (2016) 43–55

Contents lists available at ScienceDirect

Journal of Unconventional Oil and Gas Resources

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

Using experimental design and response surface methodology to model induced fracture geometry in Shublik shale

S. Poludasu *, O. Awoleke, M. Ahmadi, C. Hanks

University of Alaska, Fairbanks, United States

ARTICLE INFO

Article history:
Received 10 March 2015
Revised 26 April 2016
Accepted 26 April 2016
Available online 17 May 2016

ABSTRACT

In this study, we developed a methodology for identifying the critical variables needed for accurate planning of a hydraulic fracturing treatment in a shale resource play where much of the properties required for hydraulic fracture modeling remain unknown. The critical variables identified can thereafter be used to develop a proxy model that can be used in lieu of a numerical simulator.

This study was conducted in two stages. In the first stage, we used 2-level fractional factorial designs and a pseudo-3D simulator to identify the most important variables affecting the simulated fracture geometry. The variables investigated included geologic, mechanical and treatment design parameters. Using the three most significant variables for each fracture geometry component identified from the first stage, the second stage of this study applied Box-Behnken experimental design and response surface methodology to quantify functional relationships between input variables and the fracture geometry. These proxy models, typically polynomial equations, can be used to predict the fracture geometry with very little computational time.

The use of experimental design drastically reduces the number of simulations required to evaluate large number of variables. With only 137 simulations, 26 variables were ranked based on their statistical significance and non-linear proxy models were developed for the nine fracture geometry variables. Predicted values of the fracture geometry using the proxy models were in good agreement with the simulated values (R^2 value of 0.99 for fracture length and fracture height and R^2 value of 0.96 for fracture width). These linear and non-linear proxy models were validated by comparing the results from the proxies and the actual simulator using a random value dataset within the design space. The results indicate a good match for the width at the top and bottom of the fracture and propped fracture height/length. Engineers can use the results described here for quick estimates of fracture dimensions and the methodology outlined here can be used with more complicated fracturing models.

Introduction

The ultra-low permeability of unconventional shale reservoirs demands large-scale stimulation treatments (multi-stage hydraulic fracturing of horizontal wells) in order to produce economically. Even with the significant technological advances in modern day multi-stage fracturing, development risk has not been eliminated for developing these shale reservoirs. The risk is largely associated with the limited knowledge of reservoir geology, presence, conductivity and connectivity of natural fractures and their influence on the fracture geometry.

Typically, a hydraulic fracture design engineer uses a numerical simulator to predict the fracture geometry for a given reservoir. The choice of the simulator can vary from relatively simple and computationally inexpensive 2D models to more complex full 3D models. 2D fracture propagation models assume that an induced fracture will extend vertically to the entire height of the pay zone, and remain within the pay zone while propagating laterally (Zeng, 2002). Pseudo 3D fracture propagation models are similar to 2D models, except that the fracture height is not constrained to the payzone thickness. These models also assume that the fracturing fluid flows in one dimension (from perforations to fracture tips) to induce an elliptical fracture (Zeng, 2002). Lastly, 3D fracture propagation models have no assumptions about the orientation of the fracture. They use the local stress field and fracture mechanics criteria to estimate the fracture propagation direction (Zeng, 2002).

The choice of hydraulic fracturing model used entirely depends on the complexity of the reservoir geology and the availability of pertinent data. For simple systems, 2D equations can be used to estimate the fracture geometry. For more complicated systems, the use of either pseudo 3D or full 3D models is common or required. There is however a positive correlation between model complexity and

* Corresponding author at: 6607 Lake Woodlands Dr APT 414, The Woodlands, TX 77382, United States.
E-mail address: venkatasaisrichand@gmail.com (S. Poludasu).

http://dx.doi.org/10.1016/j.juogr.2016.04.002
2213-3976/

data requirements—as such, it is best to go with the simplest model that can fulfill the technical objectives. For a detailed treatment of existing hydraulic fracture geometry simulators, the reader is referred to the SPE Monograph on Hydraulic Fracturing.

This work is focused on the development of a methodology or workflow that identifies critical variables needed for planning hydraulic fracture treatments in shale where little geologic information is available. We also developed linear and non-linear proxies for a pseudo-3D hydraulic fracture simulator.

Given the dependence of fracture geometry on a large number of reservoir and treatment variables, using a typical numerical simulator to evaluate all the possible development scenarios would be time-intensive. Therefore, using a proxy as described above can greatly reduce the computational time and can be used to screen various scenarios. Experimental design coupled with response surface methodology is very efficient in extracting the maximum amount of information from relatively small subset of the simulation space.

Experimental designs have been widely used in petroleum engineering studies (Awoleke et al., 2012; Segnini et al., 2014; Ambastha, 2014; Yu and Sepehrnoori, 2014). In order to fully investigate the space of factorial experiments with '*n*' variables, we would require 2^n simulation experiments (full factorial design). However, as the value of '*n*' increases, the number of simulations required would also increase exponentially. If we limit our inquiry to being able to uniquely characterize the effects of each investigated variable (fractional factorial design), we can drastically reduce the number of simulations required by several orders of magnitude. The endpoint for this part of the work is to identify the statistically significant variables from our input variable set. In essence, we are using fractional factorial designs to identify and eliminate the non-statistically significant variables. We also developed a linear proxy based on the results of our simulations. However, because factorial and fractional factorial designs assume linearity, we ran another set of simulations using Box-Behnken designs and the three most significant variables (for each response variable) from the initial set of results. Using this second set of simulations, we developed a non-linear proxy. We concede that selecting only the top three significant variables would mean sacrificing some of the accuracy of the proxy for some of the response variables, as we will discuss later.

Thus, in this study, we develop some functional relationships between the fracture design variables and the predicted fracture geometry by using experimental design, a pseudo 3D simulator and data from the Shublik shale (with the Eagle Ford of Texas as an analog whenever Shublik data is unavailable) of the Alaskan North Slope. The relationships developed can be used in lieu of the numerical simulator to quickly evaluate and rank various development scenarios.

Experimental design concepts

Numerical models are widely used in engineering and scientific studies with the help of high performance computers. As a result, researchers have shifted to intricate mathematical models to simulate complex systems. The computer models often have multidimensional inputs, like scalars or functions. The output may also be multidimensional. Making a number of simulation runs at various input conditions is what is called a simulation experiment. 'Experimental design' (ED) builds a response surface which is an empirical fit of computed responses as a function of input variables. ED is an efficient way to choose the input conditions that minimize the number of computer simulation runs required for data analysis, inversion problems and input uncertainty assessment and has been used in diverse areas such as aerospace, civil engineering and electronics for analysis and optimization of complex, nonlinear systems described by computer models (Parikh, 2003). Experimental designs have also been used in petroleum engineering studies (Awoleke et al., 2012; Segnini et al., 2014; Ambastha, 2014; Yu and Sepehrnoori, 2014).

Factorial design

Consider a simulation study with 'k' input variables. Each input parameter is assigned a maximum or minimum value based on our engineering judgment. In other words, we have '*k*' input variables in two levels (a higher value denoted by '+1', and a lower value denoted by '−1'). The factorial design considers all the possible combinations of the input variables on both levels. This implies that the total number of simulations required in a factorial design with *k* factors is 2^k. This design considers all the main effects and interaction effects of all the input variables. Main effect of an input parameter is the quantification of the variation in response with change in that input parameter alone. An interaction effect signifies the relative dependence of two or more input variables among themselves based on their shared effect on the response (Parikh, 2003).

Fractional factorial design

As the number of input variables increase, the number of simulation runs required using factorial design also increases exponentially. For such cases, fractional factorial designs are utilized. This design assumes that only main effects and few of the two/three-factor interactions of input variables have significant effect on the responses. By considering, only a subset of the factorial design, fractional factorial designs drastically reduces the number of simulations required to uniquely estimate the significance all the input variables on the responses (Parikh, 2003). A disadvantage of fractional factorial designs is that it assumes linearity between the input and response variables.

Box-Behnken design

Box-Behnken design is a rotatable quadratic design based on 3-level fractional factorial design (Aslan and Cebeci, 2007). Each input factor is placed at one of the three equally spaced values, generally coded as −1, 0, +1 (lower, middle, and higher values of the input parameter range) as seen in Fig. 1. At least three levels are required for these designs as this design fits the data into a quadratic model. Since the design is quadratic, it does not assume linearity between the input and response variables.

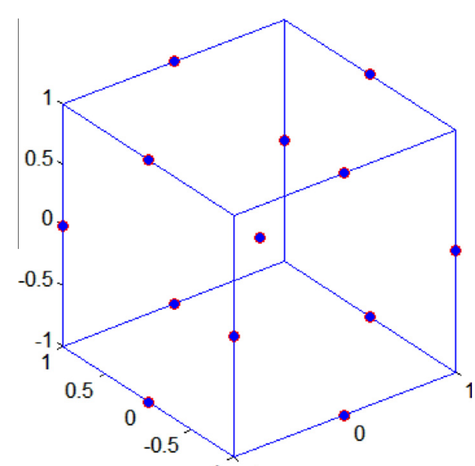

Fig. 1. Box-Behnken design.