Fuel 179 (2016) 289–298

Contents lists available at ScienceDirect

Fuel

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

A novel approach for modeling and optimization of surfactant/polymer flooding based on Genetic Programming evolutionary algorithm

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HIGHLIGHTS

- GP was used to model RF and NPV as a function of several important variables.
- 10-fold cross validation were employed to check the models overfitting.
- Simultaneous optimization was performed on both models using Design Expert software.
- Importance of all variables on both RF and NPV were investigated.

ARTICLE INFO

Article history:
Received 17 November 2015
Received in revised form 24 March 2016
Accepted 24 March 2016
Available online 1 April 2016

Keywords:
Genetic Programming
RSM
Optimization
Polymer–surfactant flooding
10-Fold cross validation

ABSTRACT

In this research, Genetic Programming (GP) as a novel method for modeling the Recovery Factor (RF) and the Net Present Value (NPV) in Surfactant–Polymer (SP) flooding is presented. The GP modeling, has the advantage that the created models did not require a fundamental description of the physical processes. The GP created mathematical functions for both outputs as a function of important parameters which involves in the SP flooding based on 202 different data. Moreover, 10-fold cross validation were employed to check the models overfitting. The Normalized Root Mean Squared Error (NRMSE) and the coefficient of determination (R^2) of 4.83%, 0.963 for the RF model, and 5.68%, 0.946 for NPV model represented the accuracy of models. The importance and effect of variables on models were investigated, and simultaneous optimization was performed on both models to find the best results in terms of higher RF and NPV. The highest values of 55.03 and 7.3 Million US Dollars (MMUSD) for RF and NPV were achieved as a result of this optimization.

1. Introduction

Polymer flooding is one of the widely used methods in Enhanced Oil Recovery (EOR), where conventional water flooding techniques are not able to provide a proper oil recovery. Since in water flooding methods, water is likely to move through the higher permeability zones and fractures, the lower permeable zones which contain significant remained oil are bypassed. This method was first presented in secondary and tertiary oil recovery during the 1960s [1], and has extensively used in operational and research applications. Addition of water-soluble polymers to water, increases the viscosity of water which results in reduction of water to oil mobility ratio. As a consequence, the sweep efficiency and the Recovery Factor (RF) increase [2]. Furthermore, less water will be required during polymer flooding compared with the common water flooding. The idea of injecting a surfactant solution was considered since 1970 to enhance the oil recovery in polymer flooding processes [3]. Surfactant–Polymer (SP) flooding consists of injection of a mixed surfactant and polymer slug followed by a polymer slug and water. During SP flooding, the role of surfactant is to lower the Interfacial Tension (IFT) between two immiscible fluids (oil and brines) [4] and alter the wettability [5], and the role of polymer is to increase the sweep efficiency in polymer and surfactant slugs as discussed earlier. Lowering IFT by surfactant causes reduction in capillary forces which enhances oil mobility, hence increases the RF [6,7]. A successful SP flooding process is the one which could well sweep the zones of interests at a cost-effective operation. Achieving this outline is significantly affected by polymer and

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http://dx.doi.org/10.1016/j.fuel.2016.03.095
0016-2361/

Nomenclature

Abbreviations

ANOVA	Analysis of Variance
BBD	Box–Behnken Design
DF	Degree of Freedom
DOE	Design of Experiment
EOR	Enhanced Oil Recovery
GA	Genetic Algorithm
GenSA	Generalized Simulated Annealing
GP	Genetic Programming
IFT	Interfacial Tension
MS	Mean Square
MMUSD	Million United States Dollars
NPV	Net Present Value
NRME	Normalized Root Mean Squared Error
R^2	coefficient of determination
RF	Recovery Factor
RMSE	Root Mean Squared Error
RSM	Response Surface Methodology
SP	Surfactant–Polymer
SS	Sum of Squares

Symbols

i	data record number
n	total number of records
y_{prd}	predicted value
y_{act}	actual value
y_m	actual values average
η	predicted response for RSM model
Z_j and Z_k	independent variables for RSM model
β_0	constant coefficient
β_j	linear coefficient
β_{jj}	quadratic coefficient
β_{jk}	interaction coefficient
ε	statistical error
X_1–X_7	input variables for SP flooding models
Y_1 and Y_2	outputs for SP flooding models
C_i	constants for SP flooding models

surfactant slug sizes, polymer concentration in polymer and surfactant slugs, surfactant concentration in surfactant slug and other factors contributing to fluid and rock properties.

SP flooding is considered as one of the chemical flooding techniques. Since, using these chemicals (surfactant and polymer) is very costly, various models are developed over past decades. Upcoming review is a brief introduction of these models. Camilleri et al. proposed a one-dimensional and compositional model to predict the oil recovery in chemical flooding [8]. Pope et al. introduced a two-dimensional, multicomponent and multiphase model for prediction in micellar/polymer flooding [9]. Hirasaki et al. presented a model based on the finite-difference in one-dimensional and six-component of surfactant flooding [10]. Barua et al. used a mathematical model for a fast calculation in chemical flooding [11]. Bhuyan et al. developed a comprehensive model for high-pH chemical floods [12]. Delshad et al. proposed a three-dimensional, multicomponent and multiphase model based on the finite difference in surfactant flooding [13]. Delshad et al. introduced a new model for fractured reservoirs [14]. Han et al. presented a fully implicit model for SP floodings [15]. Delshad et al. used a model to investigate the salinity effect in SP flooding [16]. Dang et al. developed an isotherm surfactant/rock adsorption model [17].

In the present study, a data-driven model, the Genetic Programming (GP), was employed to predict RF and Net Present Value (NPV) in SP flooding. Also, the Design of Experiments (DOE) approach was used to optimize important parameters of GP method in order to reduce the number of runs and increase the efficiency. To the best of the authors' knowledge, there is no previous study using this approach in order to assess the RF and NPV determinations in SP flooding.

2. Material and method

In this work, 202 data were obtained from Prasanphanich's M. Sc. thesis related to Benoist sand reservoir (Marion County, Illinois) [18]. The input variables are surfactant slug size (X_1), surfactant concentration (X_2), polymer concentration in the surfactant slug (X_3), polymer drive size (X_4), polymer concentration in polymer drive (X_5), Kv/Kh ratio (X_6), and the salinity of polymer drive (X_7), and the outputs are RF (Y_1) and NPV (Y_2). The NPV is evaluated at the 50 USD/bbl of oil price, and includes operation costs, chemical prices, tax, economic data and capital costs [18].

2.1. Genetic Programming

GP is one of the evolutionary algorithmic methods that was first proposed by Koza [19]. GP can generate nonlinear empirical models using the input–output data. The fundamental principles are obtained from the evolutionary Darwinian Theory, where the population progressively improves over the generations by omitting the not fitted individuals, and breeding the better children. GP is much more advanced than the other evolutionary techniques such as Genetic Algorithm (GA). GA usually does the operations on the string of numbers, and its output is a value [20] while GP operates on computer programs, and its output is a computer program. GP applies the tree representation method to show the complicated structures of computer programs, mathematical equations, or models of a process system [21]. These tree-like structures consist of a function set (nods) and a terminal set (leaves) [19]. The function set can be chosen through the operators {+, −, ×, /, sin, cos, log, abs}, mathematical functions, conditional statements or even the user defined operators. Also, the terminal set includes the

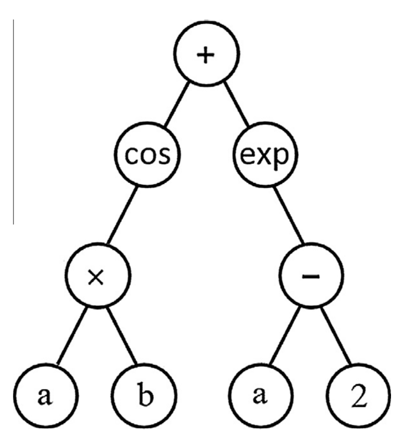

Fig. 1. Tree representation of cos $(ab) + \exp(a - 2)$.