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Reliable method for the determination of surfactant retention in porous media during chemical flooding oil recovery

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ABSTRACT

The loss of surfactant can reduce the technical and economic efficiency of chemical surfactant flooding in the recovery of residual oil. Retention of surfactant molecules is thus recognized as a fundamental problem in chemical recovery based methods. Therefore, reliable methods which are able to rapidly estimate the surfactant retention are of importance. In this communication, a new model is proposed for the determination of surfactant retention in porous media during chemical flooding. The mathematical algorithm adopted in the development of the model is gene expression programming (GEP). The input parameters for the new model are temperature, maximum effluent pH, reservoir rock type *i.e.*, carbonated or sandstone, co-solvent concentration, average molecular weight of surfactant mixture, total acid number (TAN), absolute permeability, mobility ratio, and salinity of polymer. Several statistical and graphical error analyses were applied to assess the performance and accuracy of the proposed model. A comparison was also performed between the newly developed model, a smart method, and a previously published empirical correlation available in literature. The newly developed model performs, overall, superior to the methods compared. Estimations were found to be within acceptable agreement with the literature-reported data of surfactant retention, with an average absolute relative deviation of approximately 16.6%, and a *R*-squared value of 0.92.

1. Introduction

There is a trend, recently, to continue production from mature crude oil reservoirs, most of which have been in production for many years, and to assess options for increasing the ultimate oil recovery [1]. Due to decreasing oil production in most reservoirs, a general increase in the demand for oil and oil products, concerns about the future of hydrocarbon reserves, near saturation of techniques for optimization of production facilities, and oil price volatility, there has been considerable work undertaken on enhanced oil recovery (EOR) techniques [2]. Furthermore, oil production by EOR techniques has gained attention in the petroleum industry because of their high potential for recovering larger amounts of oil from depleted reservoirs compared with conventional production methods [3].

The saturation of residual oil can be decreased if the interfacial tension existing between phases can be successfully reduced. Among chemical flooding methods for recovering oil, the use of surfactants decreases interfacial tension between oil and water, enabling recovery of much of the saturated residual oil in hydrocarbon reservoirs. After water flooding, the injection of surfactants as an oil recovery method has been implemented for more than 35 years in depleted oil reservoirs, especially in the United States of America [4–7]. Normally, surfactant injection is an expensive oil recovery method in comparison with other recovery processes like gas injection and thermal recovery techniques. However, nowadays, surfactant flooding has experienced an increase in interest because of higher oil prices [8]. In other words, effective oil recovery implementing surfactants is based on economic principles and not on whether it is technically feasible. The economic principles come down to the cost of surfactants and the development of a practical EOR process, associated with how much surfactant can be sacrificed [9]. Therefore, a better understanding of the

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Nomenclature

AAPRE	average absolute percent relative error	T	test temperature
APRE	average percent relative error	$C_{co\text{-}solvents}$	co-solvent concentration
EOR	enhanced oil recovery	S_{PD}	salinity of the polymer drive
LSSVM	least square support vector machines	pH	maximum effluent pH
GA	genetic algorithm	MR	mobility ratio
GEP	gene expression programming	MW_{Sur}	average molecular weight of the surfactant solution
GP	gene programming	RMSE	root mean square error
ET	expression tree	SD	standard deviation
R	retention of surfactant	R^2	coefficient of determination
K_{abs}	absolute permeability		
TAN	total acid number of the oil		

retention of these emulsions with crude oils is of paramount importance for progress toward EOR.

The retention of surfactant molecules is the fundamental issue and main problem recognized in chemical surfactant flooding for the recovery of residual oil. The loss of surfactant can reduce the technical and economic feasibility [10,11]. The adsorption of surfactants by porous rocks is dependent on the rock characteristics (mineralogical and morphological), type of surfactant used, and types of electrolytes existing in the solution [12]. Several studies have been undertaken in order to investigate the retention of surfactants. Standnes and Austad [13] used 14 different surfactants for spontaneous counter-current imbibition into oil-wet chalk cores by altering the wettability. They indicated that cationic surfactants can recover oil. Liu [14] conducted laboratory experiments taking into consideration the type of the rock and surfactant. Results from the study by Liu [14] indicated that anionic surfactants have much lower adsorption onto a sandstone surface than non-ionic surfactants. Yassin et al. [10] developed a model for prediction of surfactant retention by using the least squares support vector machine (LSSVM) algorithm. They used experimental dynamic surfactant retention data over a wide range of conditions. Their results indicated that the values predicted by their model were in good agreement with experimental surfactant retention data.

In recent years, smart techniques like neural networks, support vector machines, and gene expression programming (GEP) have gained considerable attention in petroleum and chemical engineering for reliable prediction of reservoir fluid properties, scale deposition, EOR processes, thermophysical properties, *etc.* [15–24]. Shafiei et al. [25] proposed a predictive method for the evaluation of the performance of the steam flooding recovery method in naturally fractured heavy oil reservoirs. They used artificial neural network modeling to predict the recovery factor and cumulative steam oil ratio. They reported that the model proposed has good potential for evaluation of the performance of steam flooding. Fathinasab et al. [26] used the genetic programming method to develop an empirical correlation for calculation of the nitrogen-oil minimum miscibility pressure. They reported that the method proposed can estimate the nitrogen-oil minimum miscibility pressure with an average absolute relative error of 10.02%. Kamari et al. [27] applied least square support vector machine for prediction of gasoline properties, viz. specific gravity, motor and research octane number (RON), and Reid vapor pressure. They obtained reasonable results for prediction of gasoline properties using the smart technique.

In a view of issues discussed above, there is still a necessity for simple, predictive, yet robust models for prediction of surfactant retention in porous media during application of the surfactant flooding recovery method. The GEP [28] mathematical approach is applied in this study to develop an accurate and reliable method for the determination of the surfactant retention in porous media during surfactant flooding. This study is organized as follows; in Section 2 we observe the influences of input/predictor variables on the retention of the surfactant. Moreover, the databank collected in this study has been presented in Section 2. In Section 3, we refer to the computational methodology pursued in this study for developing a reliable method for the determination of surfactant retention in porous media. Section 4 is organized for presenting the error parameters employed in this study for evaluation of the performance of the model developed. The results obtained with the newly developed method are presented and discussed in Section 5. In this section, the results obtained are compared with literature-reported data and a previously published empirical correlation. In order to assess the validity of the model developed for prediction of surfactant retention in porous media during surfactant flooding, several statistical parameters are considered. Moreover, the Leverage approach (Williams plot) is used to determine the applicability domain of the model and also to identify probable erroneous data points. Thereafter, future prospects and conclusions of the current study are briefly expressed in Section 6.

2. Surfactant retention

Normally, chemical EOR methods such as surfactant-based flooding techniques are applied for oils with an API gravity higher than 15 and viscosity in the range of 15-35cp and high-intermediate depths [29]. As already mentioned, the retention of surfactant plays a key role in surfactant-based EOR methods. As a matter of fact, the test temperature, maximum effluent pH, reservoir rock type, *i.e.* carbonated or sandstone, co-solvent concentration, molecular weight of surfactant mixture, TAN (total acid number of the oil), absolute permeability, mobility ratio, salinity of polymer, and surfactant formulation have considerable influence on the surfactant retention during surfactant-based flooding [30]. In the implementation of the surfactant flooding method, the abovementioned parameters can affect retention and/or adsorption of surfactant in a porous media, as listed below [10]:

- Overall, the retention of surfactant dependents on several parameters including the acidity of the oil or TAN, chemical slurry formulation, reservoir temperature, types of electrolytes present in the solution, and also type of reservoir rock.
- Alkalinity decreases adsorption of anionic surfactant on sand.
- By increasing the pH, the charge on the sand surface becomes increasingly negatively and decreases the rate of anionic surfactant adsorption.
- With regard to aqueous phase stability and microemulsion phase behaviour, an increase in temperature would affect surfactant retention for a given surfactant solution at certain conditions.