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Modeling minimum miscibility pressure during pure and impure CO_2 flooding using hybrid of radial basis function neural network and evolutionary techniques

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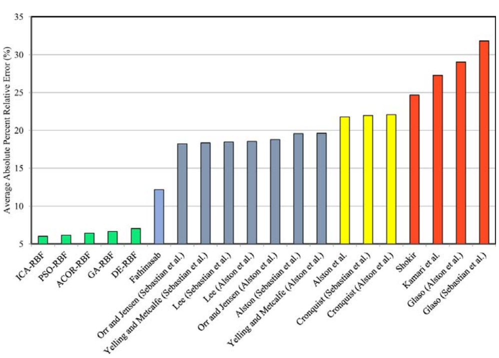
GRAPHICAL ABSTRACT



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ABSTRACT

Minimum miscibility pressure (MMP) is the most significant parameter monitoring the efficiency of CO_2 flooding by establishing the miscibility condition in the oil reservoirs resulting in a higher ultimate oil recovery factor. To date, considerable investigations on CO_2-MMP determination have been implemented; however, developing more universal models is still needed. In the present study, a number of network-based strategies, named as radial basis function neural network optimized with five evolutionary algorithms (RBF-EAs); namely genetic algorithm (GA), particle swarm optimization (PSO), imperialist competitive algorithm (ICA), ant colony optimization (ACO), and differential evolution (DE), were developed for estimating pure/impure CO_2-MMP. The most comprehensive source of data including about 270 CO_2-MMP values was utilized for RBF modeling. Crossplot, cumulative frequency diagram, and trend analysis as visual tools, and root mean square error (RMSE), average absolute percent relative error (AAPRE) and determination coefficient (R^2) as the statistical parameters, were utilized in this study to evaluate the comprehensiveness of the developed RBF tools. It was found that the ICA-RBF model is the most accurate method with statistical values of RMSE = 1.16, R^2 = 0.95 and AAPRE = 6.01%. The ICA-RBF method is more accurate than the best smart methodology developed in the literature with respect to the AAPRE parameter. Besides, temperature can be considered as the most affecting

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input data on the MMP estimations because of sensitivity analysis implemented here. In summary, the ICA-RBF mathematical strategy can provide a rapid and reasonably accurate prediction of MMP during the injection of both pure and impure streams of CO_2. The proposed strategy in this study is of paramount weight for engineers and scientist working on enhanced oil recovery.

1. Introduction

Oil production from oil fields is divided into three distinct phases: primary, secondary and tertiary, the last of which is known as enhanced oil recovery (EOR). The main aim of EOR methods is increasing recovery efficiency from depleted oil reservoirs. Generally, there are four main categories for EOR techniques: chemical flooding, thermal processes, gas injection, and microbial methods (MEOR) [1–3]. Thermal recovery processes such as, steam flooding, cyclic steam injection and in-situ combustion, use thermal energy to increase the reservoir temperature in order to reduce oil viscosity. Usually, thermal methods are used in heavy crude oil reservoirs, and using these methods for other oil reservoir types are not cost effective [4,5]. For reservoir fluids with oil API gravity higher than 25, gas injection techniques have been found to be more effective than other EOR methods such as thermal and improved water flooding. Reservoir crude oil will be faced with bypassing problem during water flooding process in the un-swept area of heterogeneous reservoirs, and this problem can be considered as an important challenge in these type of reservoirs. However, throughout the tertiary gas injection, the virgin zone fluid can effectively take part in flow because of fluid swelling and light component extraction mechanisms. When the injected phase (i.e., gas) dissolves into the displaced fluid (i.e., crude oil), the swelling of the crude oil occurs leading to the higher mobility of the reservoir fluid trapped in the porous media mainly due to offsetting capillary forces [6–12].

Among all types of gas displacing fluid, CO_2 is more frequently used than hydrocarbon gases, nitrogen and flue gas for injection purposes due to associated substantial drop in the interfacial tension (IFT) [13], oil swelling, CO_2 solubility in crude oil, and capability of component extraction. On the other hand, injection of CO_2 may cause some operational difficulties such as deposition and precipitation of asphaltene through the porous media. Nevertheless, CO_2 sequestration in geological formations such as hydrocarbon reservoirs, has been proposed to tackle the emission of greenhouse gases effectively [6–12,14].

Two different scenarios have been proposed for CO_2-based EOR including immiscible and miscible conditions. In miscible displacement, injection fluid mixes completely with reservoir fluid at any portion, and a single phase is obtained from this combination. Due to capillary pressure inherent in multiphase flow through porous media, immiscible gas injections are less effective than the other method. Miscibility condition gives more displacement efficiency for crude oil gravities more than 25° API [13]. Generally, achieving miscibility is extremely in the need of establishing multiple contacts between the in-situ crude oil and the displacing gas. For constructing such dynamic multiple contacts, it is necessary to reach a minimum value for injection pressure termed as minimum miscibility pressure (MMP) [15–17]. This important parameter is a controlling factor determining the effectiveness of any CO_2 miscible process. Inaccuracy in MMP prediction could negatively impact the total oil recovery and the operations expenditure [1,18].

For determining MMP, numerous methods have been introduced such as experimental measurement, equation of state (EOS), empirical correlations, and soft computations. Rising bubble apparatus (RBA), pressure composition diagram, vanishing interfacial tension (VIT), and slime tube are various experimental means intended for measuring MMP [17,19]. Although measuring MMP at laboratory is the most accurate technique, it suffers from some disadvantages including high cost and time length of conducting experiments and sometimes unfeasibility of measurements for all ranges of physical conditions and gas mixtures. Therefore, prediction of MMP has been appeared as a critical issue for petroleum engineers. Involving EOS in theoretical modeling makes the MMP determination highly complex. Besides, these models apply some simplification assumptions which may lead to large deviations from reality [20–22].

Hence, creating precise and simple correlations for rapid estimation of MMP is of great value leading to the extension of a large number of equations valid at diverse operational conditions. In the work of Lee [23], Metcalfe and Yelling [24] and Orr and Jensen [25], some MMP correlations were developed, in which the temperature is the only input parameter for estimating MMP. Using temperature and molecular weight of C_{7+} components, MMP value during CO_2 injection was calculated through various graphical analyses introduced by Enick et al. [26] and Holm and Josendal [27]. Considering the effect of volatile to intermediate ratio in addition to the molecular weight of C_{5+} and temperature, a commonly applied MMP correlation applicable to impure CO_2 streams, was established by Alston et al. [28]. Glaso [29] proposed another correlation to estimate CO_2-MMP when the C_2–C_6 fractions are available in crude oil. Using genetic-based calculations, a CO_2-MMP equation with the same input data used by Alston et al. [28], was proposed in the work of Emera and Sarma [30]. With the similar database employed by Emera and Sarma [30], Shokir [31] executed a well-known technique, termed as alternative conditional expectation (ACE), in order to correlate MMP with respect to a large number of input variables. In continuum, Johnson and Pollin [32] developed a comparatively sophisticated approach incorporating eight thermodynamic variables as their model input. According to a databank of 51 CO_2-MMP data for both dead and live oils, an enhanced form of MMP model was represented by Li et al. [33]. More recently, some researchers utilized various classes of genetic programming (GP) strategy to find the suitable relationships between the input parameters and CO_2-MMP for both impure and pure CO_2 streams [13,34,35].

The abovementioned correlations provide a fast estimation of CO_2-MMP; however, they are mostly established on the basis of the small-sized databank with limited ranges of input parameters. With respect to the aforementioned reservoir and thermodynamic properties, the existing models in literature cannot properly detect the present trends describing the variation of CO_2-MMP with respect to some physical conditions [36]. Accordingly, the need for development of more generalized and more accurate approaches is inevitable for CO_2-MMP estimation.

Soft computations are one of the most accurate predictive tools applicable to extremely complex and multidimensional input/output engineering problems [20–22]. In light of such smart strategies, a large number of investigations have been successfully carried out to estimate several physicochemical properties in extensive areas of chemical and petroleum engineering [22,37–41]. Moreover, some authors developed diverse intelligent schemes for determining CO_2-MMP including artificial neural network (ANN) by Huang et al. [42], least square support vector machine (LSSVM) by Shokrollahi et al. [43], radial basis function (RBF) neural network by Tatar et al. [44], hybrid of genetic algorithm and ANN (GA-ANN) by Chen et al. [45], hybrid of Levenberg-Marquardt and multilayer perceptron (LM-MLP) by Hemmati-Sarapardeh et al. [1], hybrid of adaptive neuro-fuzzy inference system (ANFIS) with several evolutionary techniques by Karkevandi-Talkhooncheh et al. [36], hybrid of mixed kernel machine and support vector regression (MKM-SVR) by Zhong and Carr [46], and other network-based methods optimized by particle swarm optimization (i.e., PSO-ANN) by Zendehboudi et al. [18] and Sayyad et al. [47]. As a matter of fact, the above