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A reliable strategy to calculate minimum miscibility pressure of CO_2-oil system in miscible gas flooding processes

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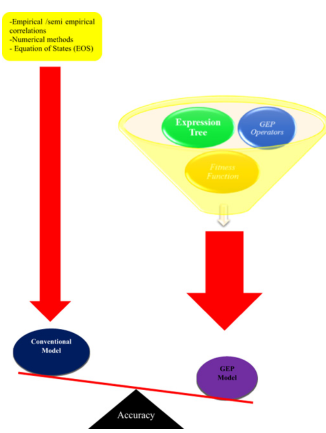
GRAPHICAL ABSTRACT



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ABSTRACT

Minimum miscibility pressure (MMP) is one of the key parameters that affects the microscopic and macroscopic effectiveness (displacement performance) of gas injection for enhanced oil recovery. Numerous research efforts have been made to measure and predict the MMP, including experimental, analytical, numerical, and empirical methodologies. Despite these efforts, a comprehensive, user-friendly, and accurate model does not exist yet. In this study, we introduce "Gene Expression Programming (GEP)" as a novel connectionist tool to determine the MMP parameter. This new model is developed and tested using a large databank available in the literature for the MMP measurements. The accuracy of the proposed model is validated and compared with the outcomes from the commercial simulators. The performance of the proposed model is also examined through a systematic parametric sensitivity analysis where various input variables such as temperature and volatile-to-intermediate ratio are considered. The new GEP model outperforms all the published correlations in term of accuracy and reliability.

1. Introduction

Gas injection is being considered as an important enhanced oil recovery method [1]. Ultimate oil recovery by gas flooding, especially CO_2 injection, into oil reservoirs can reach up to 25% of the Original Oil in Place (OOIP). The storage of CO_2 in mature and

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Nomenclature

Abbreviations

ACE	alternating conditional expectations
ET	expression tree
GA	genetic algorithm
GEP	Gene Expression Programming
GP	Genetic Programming
IFT	interfacial tension
MMP	minimum miscibility pressure
MSE	Mean Square Error
OOIP	Original Oil in Place
RBA	rising bubble apparatus
VIT	vanishing interfacial tension
EVP	extrapolated vapor pressure

Variables

MMP	minimum miscible pressure in MPa
T	the reservoir temperature in K
T_{cm}	the pseudo-critical temperature in K (note, T_{cm} in Alston et al. (1985) is in °C)
Mw	the molecular weight of C_{5+} crude
R^2	coefficient of determination
Vol.	volatile components
P_b	bubble point pressure in MPa
F_R	fraction (percentage) of components
T_R	reservoir temperature in °C

depleted oil reservoirs is one of the efficient possible methods to mitigate CO_2 emissions which favors the new regulations imposed by several governments across the world. There are a number of extensive research works in the literature that evaluate the feasibility of CO_2–EOR methods in mature oil reservoirs [2–8]. The researchers proposed different frameworks for CO_2 injection, discussed the technical and non-technical uncertainties of CO_2 injection strategies, conducted optimal CO_2 storage and EOR simultaneously, and performed risk analysis on various CO_2 injection operations. Systematic studies in the form of parametric sensitivity analysis have been conducted to investigate the effects of important variables such as the amount of injected CO_2, phase behavior of CO_2/brine/oil systems, reservoir characteristics, and minimum miscibility pressure (MMP) on the fluids displacement, production mechanisms, and operation performance over CO_2 injection processes [2–8]. Several experiences in EOR projects show that the oil recovery performance is strongly dependent on operational and capital costs, equipment/facility availability, and oil price. To have a better evaluation of injection operations prior to implementation, the uncertainties with the rock and fluids properties should be considerably lowered. Hence, determination of these important parameters with the minimum uncertainty and high accuracy can guarantee the success of the CO_2 injection processes in terms of performance, economic, and environmental prospects [2–8].

The minimum miscibility pressure (MMP) is a critical parameter in the design of gas injection facilities in which local displacement performance by CO_2 is a function of the minimum miscible pressure. The MMP in the gas-oil systems is the lowest pressure at which the crude oil will become completely miscible with the gas [9–13]. In one-dimensional displacement of two-phase flow systems such as gas and oil with a negligible dispersion, a piston-like displacement occurs when the pressure approaches MMP. In this case, the oil recovery will be very high (above 90%) after one pore volume gas injection [9–11].

The miscibility between injected gas and reservoir oil is a complicated process which is strongly affected by transport phenomena, specifically by mass transfer, pore-scale mixing, and local temperature profiles. For economic reasons, the choice of gas in the flooding operation for a given oil reservoir is based on the reservoir pressure and MMP.

Given the importance of MMP in oil production mechanisms and performance, for screening an oil reservoir for possible gas injection, an accurate mathematical model to predict the MMP will be an asset as it reduces the engineering, research, and development costs in the field of enhanced oil recovery. The aim of this paper is to develop a reliable and accurate model to easily predict the MMP parameter. To achieve this objective, we use the application of "Gene Expression Programming (GEP)" to obtain MMP. The new GEP model is developed and tested using an extensive MMP databank [14–24]. The strength of the proposed predictive model in estimating gas–oil MMP is first illustrated where the literature data are provided for the model development and comparison purposes. Then, the GEP model is used to simulate thermodynamic data/behavior for one of the northern Persian Gulf oilfields in Iran.

2. MMP determination

2.1. Empirical methods

Lee (1979) made the first attempt to estimate the MMP as a function of reservoir temperature using CO_2 vapor pressure [25]. Holm and Josendal (1974) presented a graphical MMP correlation as a function of the molecular weight of C_{5+} in the crude oil and reservoir temperature [42]. Later on, Yelling and Metcalfe (1980) developed a correlation based on the reservoir temperature to determine the MMP [21]. Johnson and Pollen (1981) introduced a MMP correlation which is a function of the reservoir temperature, and the injected gas critical pressure and temperature. The coefficients of the model are directly related to the impurity of the injected gasses [26]. Holm and Josendal (1982) developed their linear equation (presented in the form of a graph) as a function of hydrocarbons C_5 to C_{30} composition present in the C_{5+} fraction [43]. Stalk-up (1983) obtained a MMP correlation in terms of the temperature of reservoir and molecular weight of the C_{5+} fraction, based on the Cronquist's work [9,27]. Kilns (1984) correlated the MMP to the oil API gravity and reservoir temperature [28]. Orr and Jensen proposed a method to compute the MMP for low-temperature reservoirs using the extrapolated vapor pressures [29]. Glasø (1985) presented an MMP correlation by taking into consideration the effects of intermediates components (C_2–C_6) [30]. Alston et al. (1985) suggested a correlation to determine MMP by having reservoir temperature, and the molecular weight of C_{5+}, volatile, and intermediate components [14]. Sebastian et al. (1985) introduced a precise correction factor for accounting the impurity effects which depend on the average critical temperature, mole fraction, and critical temperature of the different gas components [31]. In another work, Orr and Silva (1987) obtained an equation for determination of MMP correlation where pure and contaminated CO_2 injection operations are employed [32]. Enick et al. (1988) developed a graphical correlation which is a function of the reservoir temperature and molecular weight of C_{5+} [44]. In their model, the molecular weight of C_{5+} was considered as a single alkane with an equivalent molecular weight. Wang and Orr (2000) presented a new analytical approach to determine the MMP for a displacement that includes an arbitrary number of constituents in the form of either oil or gas [13]. An analytical the-