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Full Length Article

Determination of minimum miscibility pressure in CO_2-IOR projects with the aid of hybrid neuro-fuzzy system

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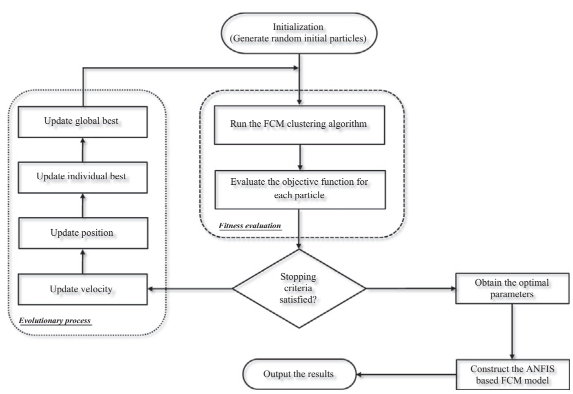
HIGHLIGHTS

- This study presents a hybrid ANFIS model by the integrating of PSO and fuzzy c-means clustering technique to determine CO_2-oil MMP.
- Reservoir temperature, crude oil composition and composition of injected CO_2 were considered as input parameters and corresponding CO_2-oil MMP information was considered as target parameter.
- Data sets related to experimental CO_2-oil MMP from the available literature were used for development of the proposed model.
- The effectiveness of the proposed model has been successfully tested by comparing with the well-known empirical correlations in published literature.

GRAPHICAL ABSTRACT



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ABSTRACT

Gas injection process is one of the most efficient improved oil recovery methods for conventional oil reservoirs. The efficiency of this process is strongly dependent on minimum miscibility pressure (MMP) which is usually determined through very expensive and time-consuming laboratory tests. So, this paper is concerned with the use of hybrid approach, combining particle swarm optimization and adaptive neuro-fuzzy inference system (ANFIS) with fuzzy c-means clustering technique, aimed at an estimation of injected gas-reservoir oil MMP. The hybrid proposed model makes ANFIS is practical in dealing with complex and high dimensional MMP problem. The process of model building is done by considering the reservoir temperature, crude oil composition, composition of injected CO_2 as input parameters and corresponding CO_2-oil MMP information as target parameter. The validity of proposed model has been successfully approved by comparing with results obtained by well-known empirical correlations in published literature. The results show that the proposed model significantly outperformed those four correlations with the lowest mean absolute error of 0.0099, the lowest root mean square error of 0.0174, and the highest coefficient of determination of 0.9823. Therefore, the proposed hybrid model can be applied as an alternative method to yield more accurate results in CO_2-oil MMP estimation.

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Nomenclature

A_{ki}	fuzzy set of the *i*th input variable in the *k*th fuzzy	P_i	best previous position of the *i*th particle
ANFIS	adaptive neuro-fuzzy inference system	P_g	best position for the whole swarm
c_1, c_2	positive constants	PSO	particle swarm optimization
D	data space	R^2	coefficient of determination
EOR	enhanced oil recovery	r_1, r_2	random numbers
$\hat{f}$	estimate of the system response	RBA	rising bubble apparatus
G_{best}	global best	RMSE	root mean square error
IFT	interfacial tension	P_{best}	personal best position
MAE	mean absolute error	V_i	velocity of the *i*th particle
MMP	minimum miscibility pressure	VIT	Vanishing interfacial tension
μ	membership function	w	firing strength
MW	molecular weight	$\bar{w}$	normalized firing strength
NN	neural network	X_i	position of the *i*th particle

1. Introduction

Gas injection is one of the most effective methods for improved oil recovery in mature reservoir fields [1]. Light hydrocarbon gas mixtures, carbon dioxide, nitrogen and flue gas mixtures are the common gases used in gas injection process. Use of carbon dioxide (CO_2) is preferred because of its lower cost, high displacement efficiency, and the potential for concomitant environmental benefits through its disposal in the petroleum reservoir [2–4].

An important concept related to the description of gas injection process is the minimum miscibility pressure (MMP). As the name implies, it is the lowest pressure at which the injected gas can achieve dynamic miscibility with the reservoir oil in multiple-contact process at reservoir temperature [5,6]. At or above MMP oil production is further improved through multiple contacts and reduction of interfacial tension between the injected gas and crude oil [6,7]. Inaccurate estimation of MMP may result unfavorable consequences. If the estimated MMP is too low, the miscible displacement would still be two phase immiscible, and consequently decrease the efficiency of the miscible displacement process.

Therefore this paper presents a novel hybrid neuro-fuzzy approach to estimate CO_2-oil MMP by considering the reservoir temperature, crude oil composition, composition of injected CO_2 as input parameters and corresponding CO_2-oil MMP information as target parameter. The outline of this paper is as follows. In the next section the MMP determination procedures and the literature is reviewed. Sections 3 and 4 give a brief overview of ANFIS model and particle swarm optimization algorithm, respectively. Proposed model is introduced in Section 5. Simulation results are provided in Section 6 to demonstrate the effectiveness and potential of the new proposed model for MMP determination compared with well-known empirical correlations using the same observed data. Finally, some conclusions are drawn in Section 7.

2. MMP determination procedures

This section provides a brief description of some of the methods used for MMP determination.

2.1. Experimental methods

2.1.1. Slim tube displacement test

Slim tube displacement test is one of the most commonly used MMP determination techniques and has been widely accepted as a standard means to measure MMP in the petroleum industry [8–10]. Slim tube is a narrow stainless-steel tube packed with sand or glass beads. The tube is filled at the beginning of each test with a known volume of reservoir sample oil. The temperature is fixed at reservoir temperature and the pressure is set at a pressure higher than the bubble point pressure. Gas is injected at the inlet of the tube to displace the oil. Several displacements are performed at rising pressures, and amount of oil recovered (typically at 1.2 hydrocarbon pore volumes of injected gas) is recorded. The miscibility condition is determined by plotting the oil recovery pressure. The pressure that corresponds to a break or sharp changes in the curve or the lowest pressure at which the recovery is about 90–95% is often considered to define the MMP.

In the this test, recoveries are under controlled condition, i.e., one-dimensional dispersion-free flow, and do not represent the recoveries in the field scale because based on reservoir heterogeneity and gravitational effects, a significant amount of the crude oil is not contacted by the gas.

2.1.2. Rising bubble apparatus

The rising bubble apparatus (RBA) involves direct visual observation of changes in shape and appearance of bubbles of injected gas rising in a visual high pressure cell filled with the reservoir crude oil. In the miscible conditions, bubble disappears at the top of column and in immiscible conditions, it is visible throughout the column. Reservoir crude oil is injected into the cell filled with distilled water to displace all water but a short column of water in the cell's bottom will remain. A small of gas is then launched into the water. As the bubble moves upward the oil, its shape and motion are monitored. A series of rising bubble tests are conducted at different pressures. The MMP is inferred from the pressure dependence of the rising-bubble behavior.

2.1.3. Vanishing interfacial tension

Vanishing interfacial tension (VIT) technique relies on the concept that the interfacial tension (IFT) between the reservoir crude oil and injected gas phases at reservoir temperature becomes zero as these two phases come close the point of miscibility [11–13]. In this method, gas–oil IFT can be measured precisely as a function of pressure and gas composition. The miscibility conditions are then determined by extrapolating the plot of IFT versus pressure or enrichment to find the pressure matching to the zero IFT value [14–16].

2.2. Computational methods

Based on the results obtained by Elsharkawy et al. [17], although the slim tube method is generally regarded as the industry standard, there is no standard design, no standard operating procedure, and no standard criterion for determining MMP with the slim tube. Moreover, to avoid undesirable effects of fingering,