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An improved Ant Colony Optimization (ACO) technique for estimation of flow functions (k_r and P_c) from core-flood experiments

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A B S T R A C T

Oil and gas production from petroleum reservoirs are significantly affected by rock and fluid properties. Relative permeability (k_r) and capillary pressure (P_c) are two key flow functions in the petroleum reservoir that are employed in numerical modeling to predict oil and gas production in future. The history matching (optimization) techniques are generally used to accurately estimate the flow functions from the results of core flood experiments.

In this study, Ant Colony optimization (ACO) method is modified for the application in the continuous inverse problem to adjust some unknown variables by either minimization or maximization of objective function. Then this technique is implemented to estimate oil, water and gas flow functions from core-flood experiments. Some new ideas and innovations are proposed to improve the performance and convergence of ACO algorithm. This algorithm is an automated history matching technique that can estimate relative permeability and capillary pressure simultaneously. Moreover, this feature enables us to incorporate different mechanisms (i.e. viscous force, gravitational force and capillary force) of the core experiments in the estimation of flow functions. Having developed the algorithm, the validity of this method is tested using two sets of coreflood experiments including gas-oil and oil-water systems. The comparison between actual values of flow functions (k_r and P_c) and those obtained from ACO method depicted good agreement and adequate accuracy. Furthermore, the investigation of objective function value versus iteration number demonstrated that the algorithm is converging to the optimal value.

1. Introduction

Relative Permeability (k_r) and Capillary Pressure (P_c) are two important properties in simulation of oil and gas reservoirs that can directly affect the fluid flow in porous media as well as oil and gas production. These parameters are named as flow function in porous media and governed by fluid saturation. Many researches have been directed toward accurate estimation of these functions in petroleum industry (Chen et al., 1999; Kerig and Watson, 1986; Schembre and Kovscek, 2006). The capillary pressure and relative permeability are not independent and one can influence the other. The simultaneous calculation of flow functions from coreflood experiment is of great importance for petroleum industry particularly in enhanced oil recovery (EOR) techniques.

Relative permeabilities curve is measured in the core laboratory by two techniques, steady state and unsteady-state experiments. In the steady state method, two immiscible fluids (e.g. water and oil) are injected cocurrently at a specific ratio through the core until the same production ratios are achieved from the outlet of the core. In this method, the relative permeability data can directly be calculated from Darcy law. However, this method has some disadvantages like being a time consuming process, unable to capture the values of low saturation and ignoring the effect of capillary forces whereas in the unsteady state method, one of the fluids is injected into the core to displace the resident fluid phases. This test is much quicker than the steady-state test but the flow functions (k_r and P_c) cannot be directly drawn from experimental results and need inverse calculation. There are two methods for estimation of relative permeability from unsteady state tests, analytical (explicit) method and optimization (implicit) method. The most common analytical method is JBN (Johnson et al., 1959) which consists of numerical differentiation of pressure and production values. In spite of simplicity, the JBN method has serious limitations including: ignoring capillary and gravitational forces, considering flow in one dimension, and assuming the fluids to be incompressible and

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isothermal. Furthermore, the numerical differentiating from experimental data points causes erroneous results in particular for data which has high fluctuation. In order to overcome the JBN limitations and obtain a more accurate flow function, the optimization or history matching technique is used. In this approach, a relative permeability and capillary pressure model are tuned in an optimization procedure to reach an acceptable match between the laboratory results of the fluid production, pressure drop and the corresponding values calculated by the model (Shahverdi et al., 2011). The optimization methods are divided into two types of deterministic (gradient) and stochastic approaches. Kerig et al. (1988) calculated the two-phase relative permeability values from unsteady state test using gradient method. Mejia et al. (1996) applied this method to predict three-phase relative permeability from coreflood experiment. The gradient optimization method originally was developed in 1963 by Levenberg & Marquardt (Moré, 1978). As the name implies the gradient methods takes derivative of the explicit objective function to find the optimal value (e.g. Newton method). The main drawback of this method is its dependency to initial guess which could lead to erroneous results when dealing with large number of unknown parameters.

The second type of optimization methods are meta-heuristic (stochastic) methods that search for the optimal value based on the stochastic algorithm. Most of these methods are inspired from rules that exist in nature. The main advantage of meta-heuristic methods is wide search domain and the ability to avoid trapping in the local optimal value. The most common meta-heuristic methods are Genetic Algorithm (GA) (Kalyanmoy et al., 2002), Ant colony Optimization (ACO) (Dorigo and Stutzle, 2004), Particle Swarm Optimization (PSO) (Riccardo et al., 2007) and so on. Meta-heuristic optimization algorithms have been used in oil industry for estimation of some scalar parameters in petroleum reservoirs (e.g. porosity and permeability of rock) but these techniques have seldom been employed for estimation of capillary pressure and relative permeability values. Razavi and Jalali-Farahani (2010) applied ACO algorithm for calculation of absolute permeability (K) and porosity (Ø) by history matching of wells pressure and well production rate. They also implemented both ACO and GA methods in a two dimensional oil reservoir model to maximize cumulative oil production by tuning the location of production and injection wells, well radius, well pressure and rate of fluid injection. They obtained a good agreement between the consequences of GA and ACO models. Hajizadeh et al. (2011) applied ACO technique for history matching of oil reservoir by tuning some unknown parameters which consists of absolute permeability and porosity. They achieved a reasonable agreement between actual parameters and those obtained by ACO. Hajizadeh et al. suggested ACO method as an efficient approach in modeling oil reservoirs. Irani and Nasimi (2012) proposed a proper hybrid of back-propagation (BP) algorithm and ant colony optimization algorithm (ACA) which could improve the performance of neural networks. They applied this new method to predict the permeability of a reservoir. The results showed that the proposed ACA-BP scheme was more efficient and effective than the BP algorithm. Zhang and Wang (2014) performed the inversion of reservoir parameters with improved niche ant colony algorithms (INACA). The method was successful at inverting porosity and permeability and it was indicated that the relative error of single parameter inversion can be maintained at less than 0.4 percent. Finally, the numerical simulation showed that the proposed INACA method is not only an effective convergent optimization method but also well suited one for solving ill-posed problems. Jung et al. (2015) presented application of ant colony optimization in estimation of the reservoir properties such as permeability, skin factor and wellbore storage coefficient from an insufficient field data. They found that the results have successfully matched to those obtained from genetic algorithm, the non-linear regression and the modified Levenberg–Marquardt method. They also proposed the ant colony method as a good way of optimization in petroleum engineering area, especially well testing analysis.

In this study, we have used ACO optimization method for simultaneous prediction of relative permeability and capillary pressure of immiscible fluids in the porous media. However, to the best of our knowledge, no researchers have been employed this approach so far in the oil industry for estimation of flow functions. Furthermore, the previous studies have mainly focused on prediction of scalar properties in oil and gas fields (e.g. pressure, porosity and absolute permeability) whereas in this study, authors estimate the flow function curves which are dependent on fluid saturation. Moreover, some significant innovations have been proposed in this study to improve the performance of the traditional ACO algorithm. The authors believe the proposed ACO in this research is more compatible with real ant behavior in nature.

The methodology of modified ACO devised in this study is described for the general optimization problem. Then the model is validated using unsteady-state coreflood experiment to estimate relative permeability and capillary pressure simultaneously.

2. Ant colony theory (ACO)

One of the most interesting types of meta-heuristic optimization techniques is ant colony optimization (ACO), which was originally developed by Dorigo (1992). This method was firstly proposed to solve the discrete space problems (e.g. Travelling Salesman Problem (Dorigo and Gambardella, 1997), Quadratic Assignment (Maniezzo and Colorni, 1999) but later was developed to solve the continuous domain problems (Socha and Dorigo, 2008; Seçkiner et al., 2013; Xiao and Li, 2011). The ACO algorithm was devised based on the behavior of ants in nature in which they search for the smallest (optimum) path between their nest and food. The investigation on the ants' life depicted that all ants leave a substance called pheromones on the pathway while moving. The amount of this substance in every path is reduced by time because of evaporation. In the other hand, the pheromone of a path is increased by those ants that passed through that particular path. Hence, the amount of pheromone in a path is controlled by two factors, the rate of evaporation and the number of ants who passed through that particular path. The pheromones left behind on the paths can be recognized by the other ants using the sense of smell such that the ants try to find those paths that have more

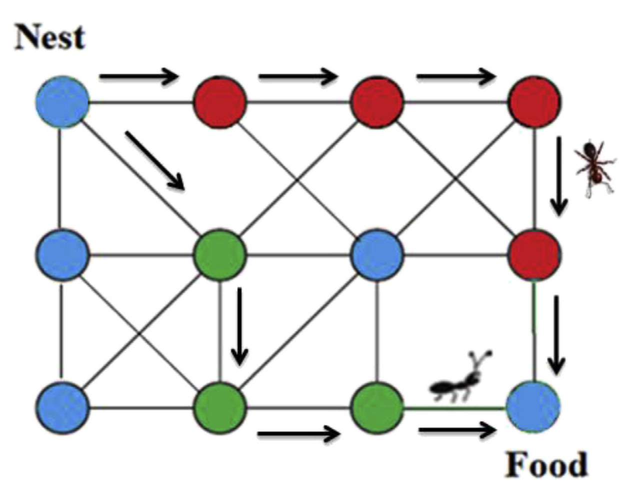

Fig. 1. Paths selected by various ants from nest to food.