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An approximate dynamic programming method for the optimal control of Alkai-Surfactant-Polymer flooding

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ABSTRACT

Since the complexity, coupling, distributed parameter, etc. of alkali-surfactant-polymer (ASP) flooding, common optimization methods cannot acquire the optimal solutions well. This paper brings an optimal control method for ASP flooding based on approximate dynamic programming (ADP). At first, take the net present value (NPV) as the performance index. Then the Actor-Critic algorithm based on gradient descent method is adopted to get the optimal injection strategy, in which Actor and Critic are used to approximate the control and value function, respectively. To improve the approximation performance, the linear approximation basis function based on system characteristic is constructed. Furthermore, to train and predict the control and value function in next step, a temporal difference (TD) learning algorithm is introduced to update the weight coefficients. Then, the control in ADP is generated according to the Gauss function and its weight is updated according to the sigmoid function of TD error, so that the optimal control can be searched. At last, the enhanced oil recovery problem of ASP flooding with four injection wells and nine production wells is solved by the proposed method to test the effect of proposed method.

1. Introduction

The continental old oil fields of China have stepped into the later stage of development, in which the moisture content is very high and the oil recovery is very low [1,2]. Traditional exploitation method cannot meet the demand of our daily life and production. Alkali-surfactant-polymer (ASP) flooding, which utilizes the synergistic effect of three displacing agents (alkali, surfactant and polymer) fully, can enhance oil recovery obviously, and has been used to improve the oil exploitation. But the research about ASP flooding is still under way. There are still many studies can be done, especially the problem of enhanced oil recovery.

ASP flooding is a kind of chemical flooding. In ASP flooding, there are always some injection wells and production wells. The flooding fluid which consists of water and displacing agents (alkali, surfactant and polymer) is injected into the reservoir through injection wells. Since the material balance law, some fluid will outflow through the production wells. Since the slow characteristic of oil reservoir filtration, the whole production period usually lasts for 5–10 years. Oil and water are two main elements of the produced fluid. The concentration of displacing agents can affect the physicochemical characteristic between oil and other ingredients of reservoir. By this way, the oil production will be changes. For ASP flooding problem, the injection concentration of displacing agents is the control variable, the water saturation, pressure and grid concentration of displacing agents are the state variables, and the moisture content of production wells is the system output. Adding the performance index such as net present value (NPV) [2], we can get an optimal control problem. The ASP flooding has the specialties of hard exploitation, long period, and slow effect [3]. A series of strict demands need to be satisfied during the whole development process. However, the essence of enhanced oil recovery is an optimal control problem. Conventional optimization method is difficult to solve this problem, since it involves a series of partial differential equations with coupling and is very complex. In engineering applications, the index comparison method is usually adopted. The basic idea is: Give many injection control strategies to the model system, simulate on the reservoir numerical simulation software to get the evaluation index, and then select the optimal control strategy according to the evaluation index artificially. This method is easy to be implemented, but it too depends on human experience and usually cannot obtain the best injection strategy. While the optimal control technology can search for the optimal

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Nomenclature

c_Θ	Concentration for displacing agents Θ
D_Θ	Diffusion coefficient for displacing agents Θ
M_Θ	Dosage constraints for displacing agents Θ
p	Pressure, MPa
Q	Volume flow rate, m^3
S_w	Water saturation
S_{or}	Residual oil saturation
φ	Porosity of the core
ρ	Density, $\mathrm{kg{\cdot}m^{-3}}$
μ	Viscosity, $\mu\mathrm{m}^2$
Θ	Mathematical set for alkali, surfactant and polymer
$\boldsymbol{\theta}$	Weight coefficient for value function approximation
$\boldsymbol{\psi}$	Weight coefficient for control strategy approximation
$\boldsymbol{\varphi}(\boldsymbol{x})$	Basis function
span $(\boldsymbol{\Phi})$	Projection matrix of global information and local information
$C(\boldsymbol{x}_t, \boldsymbol{u}_t)$	Instantaneous payoff function
$V(\boldsymbol{x}_t)$	Value function

control strategy from all feasible solutions with considering the process dynamic characteristics. It can realize the simultaneous optimization of all variables. It is suitable for the optimization of ASP flooding. Some scholars have studied on the optimal control for oil exploitation. Lei [27] presented a mixed-integer iterative dynamic programming (IDP) to optimize the polymer flooding and had got good result. Ramirez and Fathi [28] optimized the injection strategy for enhanced oil recovery of surfactant flooding with optimal control theory, in which the necessary condition of optimal control was deduced on the basis of maximum principle before solved by gradient method. Furthermore, this method was applied to carbon dioxide flooding, nitrogen flooding and binary system flooding [29]. Most of the researches are about water flooding and single chemical flooding. Very few researchers are studying the optimal control of ASP flooding. The optimal control for ASP flooding needs to be further studied, urgently. To maximize the profit, we have to seek more scientific optimization scheme.

The maximum principle, which is proposed by Pontryagin [4], is an effective method to solve optimal control problems. But for the enhanced oil recovery problem, since the mathematical model is too complex, it is too difficult to calculate the adjoint equation. The maximum principle is not so applicable. Another method, the dynamic programming (DP) [5], is usually used to solve optimal control problems. But in this method, the numerical solutions at every discrete time node have to be calculated, “the curse of dimensionality” will occur when the spatial dimension is high. Then approximate dynamic programming (ADP) is proposed to overcome this problem by approximating the value function [6,7]. But it is difficult to determine the extreme point only through value function approximation, because the strategy space is continuous. The Actor-Critic algorithm can realize the approximation of value function and control strategy simultaneously and settle the optimization in continuous space, in which the control and value function are approximated by Actor and Critic, respectively [8,9]. To improve the approximation effect, Wen et al. [10] adopted a linear approximation basis function construction method based on characteristic of system which can simplify the whole computation process.

In this paper, an ADP method for solving the optimal control of ASP flooding is proposed. In this method, the net present value (NPV) is taken as the performance index. To get the optimal injection strategy, the control and value function are approximated by the Actor-Critic algorithm which is based on gradient descent method. As to the Actor-Critic algorithm, the linear approximation basis function based on system characteristic is constructed to ensure the approximation accuracy, the weight coefficients are updated by the temporal difference (TD) learning algorithm which can train and predict the control and value function, the control in ADP is generated according to the Gauss function and its weight is updated according to the sigmoid function of TD error. At last, the proposed method is applied to solve the enhanced oil recovery problem of ASP flooding with four injection wells and nine production wells and to get the optimal injection strategy.

The paper is structured as follows. Section 2 introduces briefly the mathematical description of ASP flooding, the final optimal control problem, and the common solving method for ASP flooding. The detailed solution method of ADP is presented in Section 3. The optimal value function and control are obtained by iterative solving on the basis of Actor-Critic algorithm and temporal difference (TD) algorithm, in which the approximations are realized by the linear basis functions got from system characteristic through the proper orthogonal decomposition (POD). In Section 4, the optimal control problem of ASP flooding is solved by proposed method. The achieved conclusions are summarized in Section 5.

2. Problem formulations

2.1. Mechanism model description of ASP flooding

Basic assumptions for ASP flooding:

a) The stratum satisfies heterogeneity, the whole reservoir is isothermal, and the adsorption process complies with the Langmuir isothermal adsorption equation;
b) The oil displacement system is composed of alkali, surfactant and polymer. All displacing agents exist in water phase, while only surfactant exists in oil phase;
c) The Darcy law is fit for the flow of oil phase and water phase;
d) The phase equilibrium is set up instantly for all kinds of adsorptions which satisfy the generalized Fick’s law;
e) The fluid and rock are slightly compressible. Consider the effects of capillary force and gravity, and ignore the quality variation caused by the addition of displacing agents. Consider the permeability changes and the inaccessible pore volume of polymer.

For a reservoir with the region $(x, y, z) \in \Omega$, $\Omega \in R^3$, the main five components of ASP flooding are oil, water, polymer, surfactant, alkali. We can have below mathematical model of ASP flooding based on the research of Ge et al. in [11].

The seepage continuity equation for oil phase is

$$\nabla \cdot \left[\frac{Kk_{ro}}{B_o \mu_o} \nabla (p_o - \rho_o g h)\right] + q_o = \frac{\partial}{\partial t}\left[\frac{\phi(1 - S_w)}{B_o}\right]. \tag{1}$$

The seepage continuity equation for water phase is

$$\nabla \cdot \left(\frac{Kk_{rw}}{B_w R_k \mu_w} \nabla (p_w - \rho_w g h)\right) + q_w = \frac{\partial}{\partial t}\left(\frac{\phi S_w}{B_w}\right). \tag{2}$$

The adsorption diffusion equation for polymer is

$$\nabla \cdot \left(\frac{Kk_{rw} c_p}{B_w R_k \mu_w} \nabla (p_w - \rho_w g h)\right) + \nabla \cdot \left[(D_w + D_{wp}) \frac{\phi_p S_w}{B_w} \nabla c_p\right] + q_c = \frac{\partial}{\partial t}(\rho_r (1 - \phi) C_{rp} + \frac{\phi_p S_w c_p}{B_w}). \tag{3}$$