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Hybrid optimization technique for cyclic steam stimulation by horizontal wells in heavy oil reservoir

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ABSTRACT

With the rapid depletion of conventional oil resource, economical and efficient exploitation of heavy oil reservoirs is one of the most effective ways to meet future energy demand. This paper establishes an efficient parametric optimization method for cyclic steam stimulation (CSS) by horizontal wells in heavy oil reservoirs. The net present value (NPV) of a CSS project is maximized by optimizing operational parameters using a new hybrid optimization technique. This hybrid technique is developed by integrating uniform design (UD) into the initialization process of conventional particle swarm optimization (PSO). Case study reveals that initializing PSO with UD can improve the quality of initial particles in conventional PSO and thus speed up its convergence rate. Simulation results indicate that parametric optimization using the hybrid technique is able to obtain the best CSS development strategy for heavy oil reservoirs on both technical and economic sides.

1. Introduction

With the growing demand for hydrocarbon resources and the rapid depletion of conventional oil reserves, heavy oil reservoirs will play an increasingly important role in the future development of world economy. After decades of development, the predominant methods for developing heavy oil reservoirs are thermal oil recovery methods such as cyclic steam stimulation (CSS), steam flooding, steam assisted gravity drainage, in situ combustion and vapor extraction. CSS has been widely used because of high heat efficiency and quick effective response.

Compared with water flooding in conventional oil reservoirs, the technical and economic risk is much higher for CSS in heavy oil reservoirs due to complex geological properties and multiple flooding mechanisms. Many parametric optimization studies have been conducted since long time ago in order to improve development performance and reduce economic risk of thermal recovery projects (Escobar et al., 2000; Luo and Baker, 2006; Higuera et al., 2012; Kam et al., 2013; Zhao et al., 2013; Shakhsi-Niaei et al., 2014). There are mainly two methods used to solve this parametric optimization problem. The first one is experimental design method and the other one is production optimization methodology.

Experimental design method determines optimum operational parameters by analyzing results from a limited number of numerical simulations. It has been widely used in CSS projects. Koci and Mohiddin (2007) applied it together with Monte Carlo method to reduce simulation runs required in their study to optimize well configuration and steaming strategy. Razavi and Kharrat (2009) conducted comparative studies and a sensitivity analysis in order to find the best operational parameters for CSS by horizontal wells in Iranian heavy oil reservoirs. Liu and Gu (2012) designed an optimal set of steam quality, steam injection rate, steam injection pressure, soaking time, cyclic steam injection volume and the maximum lifting rate with the help of orthogonal algorithm. They also considered the interaction among steam quality, steam injection rate and steam injection pressure. This method can find nearly optimal operational parameters (Nguyen et al., 2011), but it is very limited in search scope and cannot explore the entire range of influence parameters due to a small number of simulation runs.

Production optimization methodology maximizes the development performance by adjusting operational parameters using

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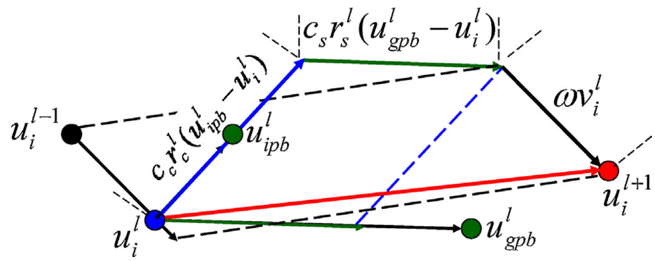

Fig. 1. Schematic for the iteration process of PSO.

Table 1
Uniform design table $U_{13}(13^{10})$.

Experiment no.	Levels of each parameter									
	1	2	3	4	5	6	7	8	9	10
1	1	2	3	4	5	6	8	9	10	12
2	2	4	6	8	10	12	3	5	7	11
3	3	6	9	12	2	5	11	1	4	10
4	4	8	12	3	7	11	6	10	1	9
5	5	10	2	7	12	4	1	6	11	8
6	6	12	5	11	4	10	9	2	8	7
7	7	1	8	2	9	3	4	11	5	6
8	8	3	11	6	1	9	12	7	2	5
9	9	5	1	10	6	2	7	3	12	4
10	10	7	4	1	11	8	2	12	9	3
11	11	9	7	5	3	1	10	8	6	2
12	12	11	10	9	8	7	5	4	3	1
13	13	13	13	13	13	13	13	13	13	13

optimization algorithms based on numerical simulations. This methodology has been successfully used in CSS projects. Revana and Erdogan (2007) presented a workflow combining reservoir simulator with economic model to optimize heavy oil recovery under uncertainty by using scatter search and tabu search methods. Patel et al. (2005) optimized oil production of a CSS project using genetic algorithm. Sun et al. (2012) applied the annealed genetic algorithm to optimize steam injection rate, steam quality, steam injection volume, soaking time and bottomhole pressure for CSS process. Azad et al. (2013) and Frenette et al. (2014) maximized the net present value (NPV) of CSS projects by optimizing soak time, cycle length and steam injection rate simultaneously with covariance matrix adaption evolution strategy. The production optimization methodology can find the global optimum with a high probability by searching iteratively the entire space of operational parameters. However, many simulations are commonly necessary and even a single run may need a very long time. In order to improve the computing efficiency, it is necessary to develop a powerful hybrid technique integrating the advantages of experimental design and optimization algorithms (Chen et al., 2010; Liu et al., 2010; Al-Gosayir et al., 2012, 2013).

Since particle swarm optimization (PSO) presented by Eberhart and Kennedy (1995) can find the global optimum with a high probability using only the estimate of objective function, it has been successfully used in petroleum engineering such as well placement optimization (Onwunalu and Durlofsky, 2010), automatic history matching (Jin et al., 2012), and steam flooding optimization (Shafiei et al., 2013). Every particle in each iteration of PSO is updated depending on its best historical experience and the overall optimal experience of the whole particle swarm. As a result, the quality of initial particles has a significant effect on the first iteration and thus on the overall convergence behavior of the PSO algorithm. The problem now is how to design the initial particles in order to improve their diversity and search scope. To address this problem, this paper introduces the uniform design (UD) method presented by Fang et al. (2000). This experimental design technique is an application of pseudo Monte Carlo method from number theory. It

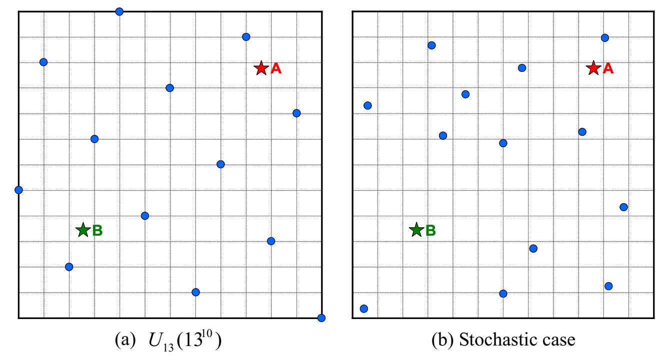

Fig. 2. Schematic for the distribution of experimental points. (a) $U_{13}(13^{10})$ and (b) stochastic case.

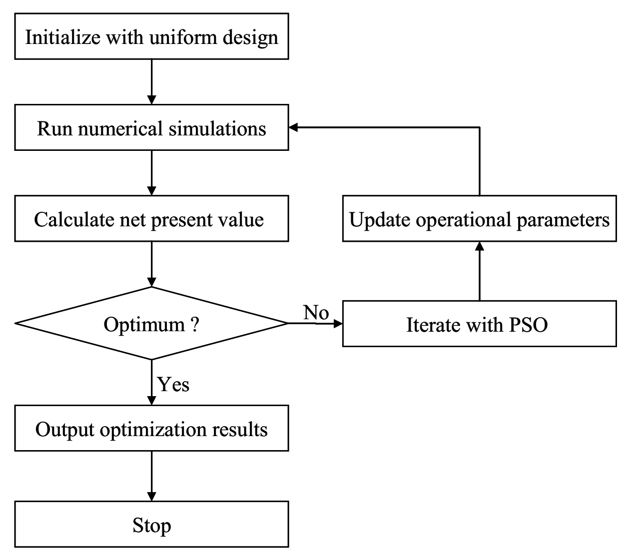

Fig. 3. Flowchart for optimization process using the hybrid technique.

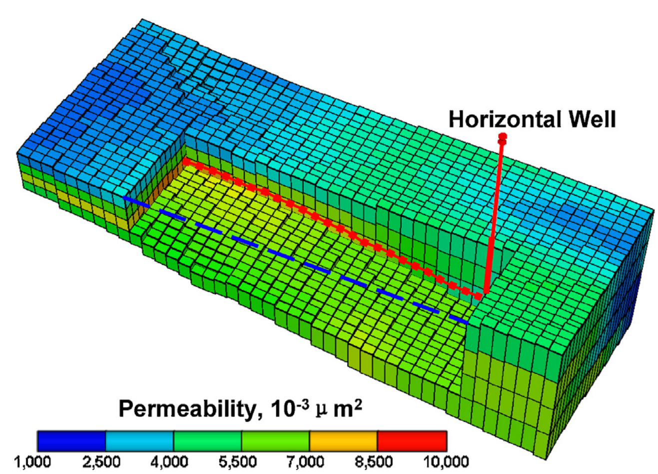

Fig. 4. The reservoir simulation model.

explains how to sample over the entire research domain in order to achieve the most information at the lowest computational cost. By integration of the UD method into the initialization process of the PSO algorithm, the paper develops a hybrid optimization technique which speeds up the convergence of conventional PSO algorithm.

Based on the hybrid optimization technique and thermal reservoir simulator (Zaydullin et al., 2014), this paper establishes an efficient parametric optimization procedure for CSS projects. It is