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In-situ recovery of heavy-oil from fractured carbonate reservoirs: Optimization of steam-over-solvent injection method

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ABSTRACT

In this paper, a hybrid global optimization framework is used to optimize the design of a new process called Steam-Over-Solvent in Fractured Reservoirs (SOS-FR) proposed by Al-Bahlani and Babadagli (2008. Heavy-oil recovery in naturally fractured reservoirs with varying wettability by steam solvent co-injection. In: Paper 117626 Presented at SPE International Thermal Operations and Heavy Oil Symposium, Calgary, Canada, 20–23 October. doi:10.2118/117626-MS), Al-Bahlani and Babadagli (2009a. Steam-over-solvent injection in fractured reservoirs (SOS-FR) for heavy-oil recovery: experimental analysis of the mechanism. In: Paper 123568 Presented at SPE Asia Pacific Oil and Gas Conference & Exhibition, Jakarta, Indonesia, 4–6 August. doi: 10.2118/123568-MS), Al-Bahlani and Babadagli (2009b. Laboratory and field scale analysis of steam-over-solvent injection in fractured reservoirs (SOS-FR) for heavy-oil recovery. In: Paper 124047 Presented at SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, 4–7 October. doi: 10.2118/124047-MS), Al-Bahlani and Babadagli (2011a. J. Petrol. Sci. Eng. 78 (2): 338–346), Al-Bahlani and Babadagli (2011b. Energy Fuels 25: 4528–4539). The hybrid framework integrates genetic algorithm with orthogonal arrays and response surface proxies for better convergence behavior and higher computational efficiency. The SOS-FR technique consists of a heating phase using steam injection, subsequent solvent injection, and low temperature steam injection for solvent retrieval and additional oil recovery. Solvent injection can be continuous or cyclic where the solvent is injected, soaked, and then fluids are produced. This paper studies both scenarios over single and multiple matrix field scaled reservoirs by adjusting the injections' durations and rates. As a result, about 30 design elements for four base benchmark models are optimized, and the profit and efficiency is doubled comparing with the benchmark models using optimal injection scheme suggested by our optimization framework.

1. Introduction

Although steam injection processes have shown acceptable production in high-permeability homogeneous sand reservoirs containing heavy-oil or bitumen, they require large amount of water to generate steam and additional treatment for re-injection or disposal (Al-Bahlani and Babadagli, 2009c). Steam assisted gravity drainage process (SAGD) is the commonly applied version of steam injection in Canada for bitumen recovery (Butler, 1994, 1997a, 1998). VAPEX (vapor extraction) process, where pure solvent is injected from a horizontal well to displace the oil via gravity drainage to a horizontal producer, was introduced by Butler and Mokrys (1991) as an alternative to steam injection.

Hybrid applications of steam and solvent were later tested to improve the efficiency of the recovery process. Expanding the solvent-SAGD (ES-SAGD) process, which is based on adding small amount of gas or liquid solvent into steam throughout steam assisted gravity drainage process (SAGD), was introduced by Nasr et al. (2003). Later, steam-alternating-solvent (SAS) technique was proposed by Zhao et al. (2005, 2007) as an application of alternative injection of steam and solvent. Adding a small amount of liquid solvent into steam during cyclic steam injection improved the recovery as demonstrated by Leaute and Carey (2007) through a pilot field project.

All these efforts were made for heavy-oil and bitumen recovery from high permeability sandstone systems. Steam injection in fractured carbonates is much more challenging and limited to a

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Nomenclature

β_i	represent a regression coefficients for one trial
β	a vector which contains all regression coefficients
CP	cooling period in phase 1
cSOR	cumulative steam-to-oil ratio (m^3/m^3)
ES-SAGD	expanding solvent-steam assisted gravity drainage
HP	heating period in phase 1
J	the actual response or actual objective function value calculated based simulation output for one trial
MRF	money recovery factor
NOA	nearly orthogonal array
RF	recovery factor
SAGD	steam assisted gravity drainage
SAS	steam-alternating-solvent
SOS-FR	steam-over-solvent for fractured reservoirs
STOIIP	stock tank oil initially-in-place
$\mathbf{u}$	a $(1*n)$ vector which contains the optimization variables for a trial.
u_i	represent an optimization variable for one trial
$\mathbf{U}$	a matrix with all $\mathbf{u}$'s

few field scale applications, mostly at a pilot level (Al-Bahlani and Babadagli, 2008; Babadagli et al., 2009). The reason behind this is the inefficiency of the steam displacement process due to heterogeneity. Alternatively, steam heating was proposed for fracture carbonate to heat and recover the matrix oil by gravity drainage rather displacing it (Macaulay et al., 1995; Snell and Close, 1999; Penney et al., 2007). The ultimate recovery from matrix in this process called thermally assisted gas–oil gravity drainage (TA-GOGD) is relatively low (Shahin et al., 2006; Babadagli and Al-Bemani, 2007) and the recovery rate is slow.

Very recently, steam-over-solvent injection in fractured reservoirs (SOS-FR) process was introduced to accelerate the recovery rate of heavy-oil and improve ultimate recovery (Al-Bahlani and Babadagli, 2008, 2009a,2009b). The process was originally suggested in three phases as follows:

- Phase I: Pre-heating by steam (or hot water) injection to recover oil by thermal expansion and capillary imbibition (if the system is water-wet) and conditioning the matrix oil for the next solvent phase.
- Phase II: Injection of solvent to dilute the oil and recover it by gravity drainage.
- Phase III: Retrieve solvent by injecting steam (or hot water) at a temperature near to the boiling point of the solvent and recover additional oil.

Different versions of this process were later tested experimentally (Al-Bahlani and Babadagli, 2012) and simulated numerically (Al-Bahlani and Babadagli, 2011a; Al-Gosayir, 2012; Al-Gosayir et al., 2013). In the numerical modeling attempts, Phase II was implemented as (1) continuous solvent injection and (2) cyclic solvent simulation which consist of three stages: (a) solvent injection, (b) solvent soaking, and (c) production. Al-Bahlani and Babadagli (2011a) showed that cyclic application gives promising results especially for multiple fracture models compared to the single matrix case. Al-Gosayir et al. (2013) optimized the cases tested by Al-Bahlani and Babadagli (2011a) and suggested the optimal injection scheme including the number and duration of the steam and solvent cycles.

The performance of this type of complex recovery process is highly impacted by a considerable number of operating parameters including steam and solvent injection rate, solvent concentration, injection pressure, and injection schedule. This requires an optimal design of the process and is commonly achieved by combined numerical simulations, sensitivity analysis, and graphical or analytical techniques. On the other hand, a limited number of studies have focused on the combination of global optimization techniques with detailed flow simulation. Gates and Chakrabarty (2006, 2008) studied genetic algorithm and simulated annealing for SAGD and ES-SAGD (expanding solvent SAGD) optimization. Peterson et al. (2010) used genetic algorithm for solvent-additive SAGD optimization. Al-Gosayir et al. (2011b) implemented hybrid genetic algorithm framework for the design of solvent-assisted SAGD processes in heterogeneous reservoirs and later applied this approach to optimizing the SOS-FR technique for huff-and-puff type applications (Al-Gosayir et al., 2013).

Many operating parameters influence the performance of the SOS-FR process such as the duration of heating period during Phase I, steam injection rate and interval, solvent cycle schedule, duration of injection and soaking cycles as well as the number of cycles in Phase II, and the steam injection rate for Phase III. With so many operating parameters, a remarkably large number of scenarios need to be tested to reach an optimal solution, which would be very exhaustive to accomplish manually. Therefore, in this paper, we tested a hybrid optimization technique introduced in our previous publication for ES-SAGD optimization (Al-Gosayir et al., 2011b, 2012a) to propose optimal application conditions that maximized the recovery and profit for the SOS-FR method. This approach was first tested to optimize the heavy oil recovery by SOS-FR method for single well (huff-and-puff) applications in our previous publication (Al-Gosayir et al., 2013). In the present paper, we applied the same approach and optimization scheme for continuous injection in different matrix size cases and compared the efficiency and economics of the project with the huff-and-puff type approach.

2. Optimization by global optimization techniques

A hybrid global optimization framework similar to that in our previous publications (Al-Gosayir et al., 2011b, 2012a) was used in this paper. This framework integrates genetic algorithm with orthogonal arrays for experimental design and response surface model as an objective function proxy. Genetic Algorithm is a population-based search technique which applies the concept of “survival of the fittest,” commonly used in the genes science (Guyaguler et al., 2002; Chen et al., 2010). An initial population or genotype is typically constructed by random sampling of the solution space or by utilizing different experimental design strategies such as orthogonal arrays. Each genotype or population has a specified number of chromosomes which contains genes. The gene is the parameter or design element such as the injection rate, while the chromosome is the group of design element that represents an operating scenario. In each evolution, the genotype is evolved where “good” chromosomes in the population with high fitness value (objective function value) are selected. These chromosomes are used as parents to create new children via crossover and mutation operations. Crossover is an operation where the offspring (child) shares genes from both parents. This can be achieved by splitting the parents’ genes into two parts and swapping these parts in the generated offspring. To improve diversity among created offspring (i.e. to ensure that the solution space has been sufficiently sampled), another genetic operation, mutation, is also performed in some of the generated offspring. Mutations change the values of some bits in one or more genes. Fitness values of these newly-constructed chromosomes are calculated and are added to the population, while the