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Multi-criterion based well placement and control in the water-flooding of naturally fractured reservoir

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ABSTRACT

In the optimization of naturally fractured reservoirs, it is required to take into account their complex flow behavior due to high conductivity fractures. In this regard, the possible effects of fractures must be included in the optimization procedure. In a water-flooding project, fast water breakthrough from injection to production wells may be occurred because of high permeability fractures. To consider the effect of the fracture system, a multi-criterion optimization procedure is proposed in this work. For this contribution, Non-dominated Sorting Genetic Algorithm version II (NSGA-II) is implemented for the optimization purposes. Considering the effect of the fracture system on the flow behavior and consequently, development scenarios, the water breakthrough time is regarded as the objective in addition to ultimate oil recovery. The procedure is applied for well placement and control problems subject to maximization of the cumulative oil production and minimization of water front velocity (or respectively maximization of water breakthrough time). The problems cover design of well configuration and also time-varying bottom-hole pressures. Geological fracture uncertainty in terms of fracture permeability realizations is taken into account for the last optimization problem. This enables decision-makers to select the best scenario by a trade-off between the objectives which are maximization of expected reservoir performance and reducing the risk associated with the worst-case scenario. For this optimization problem under uncertainty, the significance of water breakthrough time expected value as an objective on the robust optimization problem is investigated.

1. Introduction

A key component of the reservoir management is to take decisions about the future life of subsurface oil and gas resources (Jansen et al., 2008, 2009; Sarma et al., 2006; Shirangi and Durlofsky, 2015; Wang et al., 2007). Decision making generally entails optimization of development scenarios based on the reservoir model whose performance in the prediction of future is reliable. Reservoir development optimization may require to determine the well location, injection/production patterns, and also time-varying controls. There are recently many researches about the joint and sequential well placement and control optimization (Afshari et al., 2015; Ahmadi and Bahadori, 2015; Carosio et al., 2015; Feng et al., 2015; Humphries and Haynes, 2015; Siavashi et al., 2016; Zandvliet et al., 2008). In the literature, many works have been addressed to cover some aspect of the general reservoir development optimization. Cumulative oil production (COP), net present value (NPV), production plateau time (PT), and voidage replacement ratio (VRR) are among the most-used criteria in the production optimization (Almeida et al., 2007; Awotunde and Sibaweihi, 2014; Bellout et al., 2011; Brouwer and Jansen, 2004; Doublet et al., 2009; Echeverría Ciaurri et al., 2011; Forouzanfar and Reynolds, 2013; Gross, 2012; Humphries et al., 2014; Isebor and Durlofsky, 2014; Obiajulu J Isebor et al., 2014a, 2014b; Li and Jafarpour, 2012; Li et al., 2013; Lorentzen et al., 2006; Onwunalu and Durlofsky, 2010; Van Essen et al., 2011; Zandvliet et al., 2008).

Almost, a single optimization approach has been implemented in all the mentioned works. In the real practice, the aim is to find an optimum design satisfying multiple objectives, which may be possibly conflicting. To deal with these objectives, multi-objective optimization algorithms can be used. It provides a set of optimal solutions represents the trade-off between the multiple objectives. Each solution of this set which is named Pareto front (Rao, 2009) can be considered as optimal scenario for reservoir development based on the weighted average of objectives.

Although some previous works have been addressed in the application of multi-criterion optimization in the petroleum engineering literature, most of them are focused on the history matching problems. In this regard, multi-objective optimization has been used when

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Nomenclature

B	formation volume factor
BHP	bottom-hole pressure
BT	breakthrough time
COP	cumulative oil production
CWI	cumulative water injection
CWP	cumulative water production
E	expected value
f	objective function
k	relative permeability
min	minimum value
N	number of objectives (in this work N=2)
n	number of optimization variables
NPV	net present value
P	pressure
q	flow rate
S	saturation
t	time
TR	transmissibility
u	optimization variables (in this work, well locations and controls)
φ	porosity

Subscripts

f	fracture domain
i	objective count
m	matrix domain
mf	matrix/fracture interaction
o	oil phase
r	relative permeability
w	water phase

Superscripts

L	lower bound
U	upper bound

multiple misfit criteria are used to update the reservoir model (Christie et al., 2013; Ferraro and Verga, 2009; Hajizadeh et al., 2011; Mohamed et al., 2011; Sayyafzadeh et al., 2012). Recently, some efforts have been done to apply the multi-objective approach for the production optimization problems. Gross (2012) maximized different objectives such as oil recovery factor and production plateau time based on a decision framework using the multi-objective optimization. Independent variables in their optimization problem were number of wells and their plateau rates. Yasari et al. (2013) designed a well control problem under the geological uncertainties. They applied the multi-criterion optimization to satisfy maximize/minimize components of NPV using Non-dominated Sorting Genetic Algorithm version II (NSGA-II proposed by Deb et al. (2002)). Awotunde and Sibaweihi (2014) implemented weighted sum multi-objective well placement problem to maximize NPV considering VRR as the secondary objective. Isebor and Durlofsky (2014) developed a hybrid optimization algorithm named BiPSO-MADS (Bi-objective Particle Swarm Optimization – Mesh Adaptive Direct Search). They tested this algorithm for the general oil field development considering well number, type, location, and control with/without model uncertainties. Yasari and Pishvaie (2015) used multi-objective approach for the robust optimization of the injection policies during water-flooding under the geological model uncertainty. The expected value and standard deviation of NPVs (corresponding to different geological realizations) are their objectives. To capture the "uncertainty" and preserve "variability" of realizations, they proposed two different multi-objective optimization using NSGA-II.

To the author's knowledge, production optimization in the naturally fractured reservoirs is not well discussed. Most of the efforts in the fractured reservoir management are focused on the history matching problem (Ghaedi et al., 2015a, 2015b, 2015c; Ghods and Zhang, 2010; Nejadi et al., 2012; Ping and Zhang, 2013; Tanaka et al., 2010). In the modeling of naturally fractured reservoirs, the dual porosity concept is commonly used approach (Aguilera, 1980; van Golf-Racht, 1982; Warren and Root, 1963). In this model, two distinct sets of physical parameters for the fracture and matrix are defined. Due to complexity of the fracture nature, cautious should be exercised for the subsurface modeling, optimization, and planning in these reservoirs. High conductivity of fractures may cause that water breakthrough from the injection to production wells happens in early time of the injection period. This not only reduces the ultimate oil recovery but also increases the cost due to the excessive amount of production/injection water (Ahmadi et al., 2014). In this regard, development scenarios such as well location and well controls should be optimized to postpone the water/gas breakthrough. This entails that wells produce below a critical rate (Saad et al., 1995; van Golf-Racht, 1982) which can conflict with the ultimate recovery in a predefined life cycle of the reservoir.

This work addresses application of multi-objective approach to consider the effect of fracture conductance on the production scenario efficiency during the water injection process. In this regard, NSGA-II proposed by Deb et al. (2002) is used to maximize the production performance. Our optimization is based on two conflicting objectives: maximizing the cumulative oil production (COP) during the reservoir life cycle and delaying the injection to production breakthrough time (BT). Final optimal solution set (Pareto front) provides different solutions for decision-makers to select the production scenario by trade-off between objectives.

This paper is structured along the following lines: in the Section 2, after brief description of the problem, the methodology for multi-objective optimization based on the NSGA-II is illustrated. Three case studies on a synthetic dual porosity reservoir are presented in the Section 3. These examples demonstrate the application of multi-criterion optimization to maximize the oil production as well as delay the water breakthrough time. We also implement the methodology to a problem involving uncertainty in the fracture permeability. Finally, concluding remarks are provided in the Section 4.

2. Methodology

2.1. Multi-objective optimization

The goal of this work is to optimize development of naturally fractured reservoirs during the water-flooding process. To cope with this, multiple conflicting objectives should be satisfied. Generally speaking, a multi-objective problem may be presented in the following form:

$$\begin{cases} \mathit{maximize/minimize}\ \underline{\boldsymbol{f}} = [f_1(\boldsymbol{u}).\ f_2(\boldsymbol{u}).\ \dots f_N(\boldsymbol{u})] \\ \mathit{subject\ to}\!:\ u_i^L \le u_i \le u_i^U \qquad\qquad i = 1.2.\ \dots.n \end{cases} \quad (1)$$

where $\underline{\boldsymbol{f}}$ is the vector of N conflicting objectives; each of these objectives may be maximized or minimized. $\boldsymbol{u}$ is optimization manipulating variables whose size depends on the specific problem. In the reservoir development problem of this work, it consists of discrete (well locations) and continuous variables (well time-varying controls).

The interesting point of multi-objective optimization for the reservoir management is that, it provides a clear and quantitative picture of the optimum trade-offs between multiple conflicting objectives. This optimal solution set is named Pareto front; it enables