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Sensitivity analysis and optimal operation control for large-scale waterflooding pipeline network of oilfield

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ABSTRACT

Waterflooding development is one of the most common methods in oilfields. The energy consumption of waterflooding system accounts for a large proportion of the total in oilfield development. Therefore, the optimization of waterflooding system is able to further decrease operation cost and enhance development efficiency. But it is complicated to optimize operation control of large-scale waterflooding pipeline networks as a result of lots of wells and complex waterflooding pipeline networks. Although previous scholars have done much research, few have considered technical constraints of waterflooding networks. This paper puts forward a quantitative evaluation approach to pressure and flowrate sensitivity of waterflooding pipeline networks firstly, and concludes that the pressure and flowrate sensitivity are related to network topological structures, pipeline parameters and current operation flowrates. Meanwhile, an operation optimization approach to large-scale oilfield waterflooding system based on mixed integer linear programming (MILP) is proposed, which considers pump characteristic curves, adopts Hazen–William formula to simulate hydraulic pressure drop of pipe segments and deals with nonlinear items by phased linearization method. With the demand flowrate, the optimal pumping scheme of waterflooding station, pumping flowrate and throttling pressure of each well can be efficiently worked out. Finally, this approach is successfully applied to a virtual waterflooding system with 15 wells and a large-scale real one with 82 wells in China. Results show that the model has better practicality for the operation control optimization of waterflooding pipeline networks with larger scale and stronger sensitivity.

1. Introduction

1.1. Background

Waterflooding is one of the most common methods in oil reservoir development. Water is injected back to reservoir to maintain the reservoir pressure and enhance oil recovery (Xu et al., 2015; Chang et al., 2016). Waterflooding system is composed of waterflooding stations, water distribution stations, waterflooding wells and pipelines and the fittings that connected them. It is a continuous and closed hydraulic system and a complex system (Zhang et al., 2016; Price and Ostfeld, 2016). Waterflooding system optimization contains distribution (Izquierdo et al., 2015), operation (Menke et al., 2016; Yazdi et al., 2016) optimization, etc. Some sub-optimization problems belong to NP-hard problems (Lansey and Awumah, 1994). Traditional optimization approaches cannot reach the optimal results and most in-situ waterflooding pipeline network optimizations are empirically designed.

Mostly, previous researchers took their attention on the optimization of waterflooding flowrate and pressure (Yasari et al., 2013; Hourfar et al., 2016; Horowitz et al., 2013). Few of them have taken the transportation process of water into consideration. There is hydraulic interact among waterflooding pipelines, waterflooding stations and waterflooding wells as a whole pressure system (Jowitt and Germanopoulos, 1992). How to regulate each equipment to reach the optimal waterflooding flowrate of each well under technical and equipment constraints is a tough problem (Napolitano et al., 2016; Li and Zhou, 2016). Meanwhile, waterflooding is one of the major costs of oilfield operation. Failure to optimize the operation parameters under complex connection network can cause invalid migration of water in the pipeline, and thus waste energy and cause potential safety hazard (Chang, 2001; Rimkevicius et al., 2012).

1.2. Related work

To the best of our knowledge, there are few articles about waterflooding pipeline network optimization. Cong-Xin (2001), Guan et al.

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Nomenclature

Sets and indices (The set of)

$i \in I$	number of node
IP	number of pump station node $IP \subset I$
IW	number of well node $IW \subset I$
$h \in H$	number of point (point is made up of nodes)
$j \in J$	number of pipeline segment
$a \in A$	number of range of flow rate
$k \in K_i$	number of pump operating scheme at node i (when i is a pump station)

Continuous parameters

C_E	electricity price
$Q_{\mathrm{Amin}a}$	lower bound of flow rate range a
$Q_{\mathrm{Amax}a}$	upper bound of flow rate range a
$a_{i,k}$, $b_{i,k}$	head formula parameter of pump operating scheme k at node i.(when i is a pump station)
$Q_{\mathrm{APmin}i,k}$	lower bound of the flow rate when starting the pump of pump operating scheme k at node i.(when i is a pump station)
$Q_{\mathrm{APmax}i,k}$	Upper bound of the flow rate when starting the pump of pump operating scheme k at node i.(when i is a pump station)
$Q_{\mathrm{Pmax}j}$	upper bound of the allowed flow rate at pipeline j.
$Q_{\mathrm{Fmax}i}$	upper bound of the allowed flow rate at influx point i (when i is a well).
$Q_{\mathrm{Fmin}i}$	lower bound of the allowed flow rate at influx point i (when i is a well).
$P_{\mathrm{Wmin}i}$	lower bound of the allowed pressure at influx point i (when i is a well).
$P_{\mathrm{Wmax}i}$	upper bound of the allowed pressure at influx point i (when i is a well).
α_i, β_i	coefficient of the injectivity index equation

Binary parameters

$B_{\mathrm{PPI}i,j}$	$B_{\mathrm{PPI}i,j} = 1$ if node i is the starting point of pipeline j.
$B_{\mathrm{NPI}i,j}$	$B_{\mathrm{NPI}i,j} = 1$ if node i is the ending point of pipeline j.
$B_{\mathrm{M}i,h}$	$B_{\mathrm{M}i,h} = 1$ if node i belongs to influx point h.
$B_{\mathrm{W}i}$	$B_{\mathrm{W}i} = 1$ if node i is a well.

Continuous variables

$E_{\mathrm{P}i}$	output power at node i (when i is a pump station).
$Q_{\mathrm{D}i}$	required injected water flow rate at node i (when i is a well).
$Q_{\mathrm{P}i}$	actual injected water flow rate at node i (when i is a well).
$Q_{\mathrm{S}i}$	injected flow rate by pump at node i (when i is a pump station).
$Q_{\mathrm{PI}\,j}$	flow rate at segment j.
P_i	pumping pressure at node i.
$P_{\mathrm{FA}\,j}$	actual friction loss along segment j.
$P_{\mathrm{J}i}$	throttling flowrate of node i (when i is a well)

Binary variables

$F_{\mathrm{QP}i,k,a}$	$F_{\mathrm{QP}i,k,a} = 1$ if flow rate at node i(when i is a pump station) is within a range and the pump operating scheme k.
$F_{\mathrm{P}i,k}$	$F_{\mathrm{P}i,k} = 1$ if node i(when i is a pump station) is under the pump operating scheme k.
$F_{\mathrm{QF}j,a}$	$F_{\mathrm{QF}j,a} = 1$ if flow rate at segment j is within the range a.

(2005) and Yang et al. (2006) used heuristic algorithms and improved genetic algorithms to solve this problem; however, the work simplified the model and failed to contain many technical constraints and had no discussion on the optimization of the results. Thus these methods have errors in real application. Previous researches have been done based on reservoir models and worked out the optimal waterflooding flowrate and pressure at each wellhead (van Essen et al., 2009). Almeida et al. (2010) took intelligent well control as a valve control, considered the uncertainty of technic and reservoir, built an optimal model with the maximum net present value as the objective function and solved the model by using genetic algorithms. Chen and Hoo (2012) used Markov chain Monte Carlo and an ensemble Kalman filter models to determine the nondeterministic parameters and built the optimal model. However, the two models only considered the formation water driving process but failed to consider the in-situ application of the optimal results.

However, many researches have been done on products pipeline network (Zhou et al., 2014) and water distribution system (Costa et al., 2016) optimization, and the results could be beneficial for waterflooding system. Sterling and Coulbeck (1974) proposed an hierarchical Lagrangian dual method to solve the water supply pipeline network optimization problem. Mccormick and Powell (2003) considered the maximum demand charges, solved the water pump dispatching problem by using stochastic dynamic program. Shu et al. (2010) used hybrid genetic algorithm (genetic simulated annealing, GSA) to automatically determine the least-cost pump operation for each pump station in large-scale water supply system while satisfying hydraulic performance requirements. Lan et al. (2016) proposed a non-convex nonlinear model and solved the above problem by a branch-and-reduce global optimization approach. Zhuan and Xia (2013) came up with a reduced dynamic programming algorithm for pumping optimization, which was verified by real cases. Olszewski (2016) performed an energy optimization of four-pumps systems in parallel configuration, considering various energy-related strategies, and used genetic algorithm (GA) to minimize the power consumption in pumping station. Bonvin et al. (2016) put forward a convex mathematical program to work out pumping optimization of the water distribution system. The model was characterized by fast solving and strong convergence so that the global optimal solution could be obtained, which effectively dealt with optimal pumping scheme of distribution networks. Yet few researches have chosen mixed integer linear programming (MILP) method to solve this problem.

Even though the optimization of water distribution system is similar with waterflooding system, it has different distributions and connections from that of water distribution system in virtue of the waterflooding pipeline network constrained to technic. Thus, some of the heuristic algorithms can no longer be applied to waterflooding networks. In this way, the above methods cannot be used for waterflooding system operating optimization.

This paper proposes an optimal waterflooding system operating scheme by MILP method, taking the minimum operating cost as the objective function and waterflooding apparatus, technic and demand flowrate as constraints.

1.3. Contributions of this work

- This paper proposes a quantitative evaluation approach to pressure and flowrate sensitivity of waterflooding pipeline network.
- This paper proposes a MILP method to solve the waterflooding system operating optimization.
- The proposed method can work out the global optimal parameters of each waterflooding apparatus.