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D-optimal design for Rapid Assessment Model of CO_2 flooding in high water cut oil reservoirs

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A B S T R A C T

Most of major oilfields in China have reached high water cut stage, but still, they contribute to more than 70% of domestic oil production. How to extract more oil from mature oilfields has become a hot topic in petroleum engineering. Carbon dioxide flooding is a win–win strategy because it can enhance oil recovery and simultaneously reduce CO_2 emissions into the atmosphere. In order to evaluate the potentials of CO_2 flooding in high water cut oil reservoirs, various 3-D heterogeneous geological models were built based on Guan 104 fault block in Dagang Oilfield to perform reservoir simulations. The D-optimal design was applied to build and verify the Rapid Assessment Model of CO_2 flooding in high water cut oil reservoirs. Five quantitative variables were considered, including average horizontal permeability, permeability variation coefficient, ratio of vertical to horizontal permeability, net thickness of formation and percentage of recoverable reserves by water flooding. The process of weighting emphasized the contributions of linear terms, quadratic terms and first-order interactions of five quantitative parameters to improved recovery factor and Net Present Value of CO_2 flooding. Using the Rapid Assessment Model of CO_2 flooding in high water cut oil reservoirs, significant first-order interactions were sorted out and type curves were established and analyzed for the evaluation of technical and economic efficiency of CO_2 flooding in high water cut oil reservoirs. Aimed at oil reservoirs with the similar geological conditions and fluid properties as Guan 104 fault block, the Rapid Assessment Model and type curves of CO_2 flooding in high water cut oil reservoirs can be applied to predict improved recovery factor and Net Present Value of water-alternating-CO_2 flooding at different conditions of reservoir parameters and development parameter. The approach could serve as a guide for the application and spread of CO_2-EOR projects.

1. Introduction

CO_2 flooding has been widely applied as an effective EOR technology around the world (Awan et al., 2008; Bogatkov and Babadagli, 2009; Liao et al., 2012; Ren et al., 2011). Its features of oil viscosity reduction, oil volume swelling and interfacial tension reduction could greatly improve microscopic oil displacement efficiency (Orr et al., 1982; Qin et al., 2010a,b; Yang and Gu, 2008). Meanwhile, carbon sequestration in the process of CO_2 flooding makes this approach more meaningful to the environment (Wang et al., 2009). As a famous field application, Weyburn CO_2-EOR project has a total storage capacity of 2000×10^4 tons of CO_2 (Malik and Islam, 2000).

Theoretically, CO_2 miscible flooding could provide a microscopic oil displacement efficiency of over 90%; however, CO_2 flooding cannot enhance oil recovery much in field applications due to gas channeling and poor sweep efficiency. Injecting water slug along with gas slug, i.e., water-alternating-gas (WAG) flooding, can reduce relative permeability to gas in porous media and thus lower the total mobility. Therefore, CO_2 WAG flooding is regarded to recover more oil than continuous injection flooding (Caudle and Dyes, 1958; Christensen et al., 2001). Seright (1995) developed a

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coreflood apparatus to reveal different types of gels can selectively reduce permeability to gas more than to water and this characteristic could be stable to repeated WAG cycles. Hence, gel treatment can be applied to reduce channeling in high-pressure gas flooding. Zhao et al. (2014) chose ethylenediamine for permeability profile control during CO_2 flooding. Experimental results showed oil recovery was significantly improved because gas channeling was mitigated or prevented.

Not all hydrocarbon reservoirs are favorable to the implementation of CO_2 flooding. CO_2 resource is a key factor to carry out CO_2-EOR projects. Currently, the main injected-CO_2 is from natural gas reservoir with high concentration of CO_2 or CO_2 reservoir (Grigg and Schechter, 1997; Sahin et al., 2012). The implementation of CO_2-EOR projects could offset the cost of CO_2 separation from natural gas. Therefore, this technology is conducive to both natural gas exploitation and environmental protection.

Based on field project details, screening criteria were proposed for the ranking of oil reservoirs suitable for CO_2 EOR. Taber et al. (1997) developed screening criteria for all EOR method including CO_2 flooding, and then the criteria were updated by Aladasani and Bai (2010) with additional field results reported at SPE conferences from 2007 to 2009. Except for reservoir depth and oil viscosity, all screening parameters specified by Taber et al. (1997) can be used to rank oil reservoirs for CO_2 EOR under the updated criteria. Focusing on CO_2 miscible flooding, a selective criterion was presented by expanding database distributions and offering correlations of reservoir properties reported in field projects. Furthermore, a prediction model of incremental recovery was generated for miscible CO_2 projects (Aladasani et al., 2012). Besides, integrated application of reservoir simulation and experimental design provides a novel research idea to establish criteria for screening candidate reservoirs. Yao and Ji (2010) built a quick evaluation model for CO_2 storage potential and oil recovery as a function of several dimensionless variables through a Box–Behnken design, and performed sensitivity analysis of each variable. Ghomian et al. (2008) conducted an economic analysis and established equations of CO_2 credits for different reservoir types by using fractional factorial design and response surface methodology. For quick screening candidate thin reservoirs for different production strategies, D-optimal design was used by Kabir et al. (2008) to derive useful phenomenological correlations of oil recovery and emphasize contributions of different variables to oil recovery in the process of weighting.

In order to discern feasibility of CO_2 flooding in a water flooded reservoir, Qin et al. (2010a,b) has proved CO_2 is able to displace the residual oil that is immobilized by water flooding and therefore improve the microscopic displacement efficiency by conducting visualized experiments. Through a simulation study on field models, Jahangiri and Zhang (2011) revealed CO_2 injection after water flooding can enhance oil recovery for both immiscible case and miscible case. In previous study, technical and economic analyses of reservoir parameters and development parameters were conducted on CO_2 flooding in high water cut oil reservoirs by performing simulation runs (Song et al., 2014). However, when feasibility of CO_2 flooding is being estimated, some unavailability may exist for running numerical simulation on a target reservoir, and also, reservoir simulation is time-consuming and less cost-effective. Therefore, a mathematical model is essential to predict reservoir performance and judge the feasibility of CO_2 flooding in high water cut oil reservoirs.

The main objective of this paper is to build Rapid Assessment Model for the feasibility study of CO_2 flooding in high water cut oil reservoirs. Reservoir simulations were performed on various geological models that were built based on Guan 104 fault block in Dagang Oilfield. By taking into account five quantitative parameters, Rapid Assessment Model of CO_2 flooding in high water cut oil reservoirs was created and verified by implementing D-optimal design. The weighting of linear terms, quadratic terms and first-order interaction of five parameters was emphasized on improved recovery factor and Net Present Value of CO_2 flooding. Besides, type curves were generated and analyzed for the evaluation of technical and economic efficiency of CO_2 flooding. This approach could serve as a guide for the application and spread of CO_2-EOR projects in high water cut oil reservoirs.

2. Reservoir description

Based on a reservoir on Guan 104 fault block in Dagang Oilfield in China, a base reservoir model was built with the initial formation pressure of 272.1 bars. The depth of the top of the reservoir is 2700 m, and the average horizontal permeability is 300 md. The base reservoir model includes nine five-spot patterns with a well spacing of 300 m and contains $37 \times 37 \times 4$ grid blocks with the x, y and z dimensions of 25 m, 25 m and 2.5 m, respectively. The average porosity is 19.04% and the original oil in place (OOIP) is 68.92×10^4 ton. Eclipse Compositional Simulator was utilized to perform water flooding and CO_2 water-alternating-gas flooding. The pseudo-components of crude oil and relative permeability curves were described in details in the literature (Song et al., 2014). The minimum miscibility pressure between the reservoir oil and CO_2 was determined to be 322.8 bars by slim-tube experiments, which means CO_2 immiscible flooding was conducted in this case.

3. D-optimal design schemes

In order to build Rapid Assessment Model of CO_2 flooding in high water cut oil reservoirs, five quantitative parameters were taken into account with their four levels of uncertainty in Table 1. Average horizontal permeability k, permeability variation coefficient v_k, ratio of vertical to horizontal permeability k_v/k_h and net thickness of formation h were discussed as reservoir parameters. Their four levels were assumed based on the range of main parameters of Guan 104 fault block. Percentage of recoverable reserves by water flooding R_{wf} was considered as development parameter. This term indicates what percentage of maximum water flooding recoverable reserves have been already extracted before CO_2 WAG flooding is implemented in the target oil reservoir. This parameter was considered to optimize CO_2 injection timing in a water flooding reservoir. 100% of recoverable reserves by water flooding mean that all the producers reach the water cut of 98% to shut in. In a full factorial design (i.e., all combinations of multiple parameters with multiple levels are investigated), 4^5 schemes will be required. Obviously, it would increase experimental executives and computational cost.

As a class of designs of experiments, D-optimal design allows parameters to be estimated without bias and with minimum variance (Smith, 1918). Meanwhile, this approach requires a few experimental runs to estimate parameters with the same precision

Table 1
Five quantitative parameters and their four levels of uncertainty discussed in Rapid Assessment Model of CO_2 flooding in high water cut oil reservoirs.

Level	Quantitative parameter				
	Average horizontal permeability, md	Permeability variation coefficient	Ratio of vertical to horizontal permeability	Net thickness of formation, m	Percentage of recoverable reserves by water flooding
1	200	0.5	0.1	10	40
2	300	0.6	0.2	20	60
3	400	0.7	0.3	30	80
4	500	0.8	0.4	40	100