Optimization of Oil Production in CO_2 Enhanced Oil Recovery

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Abstract Oil production have several stage i.e. primary, secondary and tertiary. In tertiary stage, the effort to increase oil production is called as enhanced oil recovery (EOR). EOR is performed by injecting material or energy from outside reservoir. There are several EOR methods that have been developed and implemented in the oil field, including thermal recovery, chemical flooding, and solvent flooding. One of solvent flooding is CO_2 EOR by injecting CO_2 to reservoir. CO_2 EOR method has capability to increase 5–15% oil recovery. In addition, injecting CO_2 to reservoir have good impact to reduce global warming effect. However, to obtain the optimum result of CO_2 EOR needs several parameter to be optimized, such as mass flow rate, pressure and temperature injection. There are several equation that have been used to build a model of CO_2 EOR pressure drop. There are Fanning equation for injection well, Darcy equation for reservoir formation and Beggs-Brill equation for production well. The model has been validated using PIPESIM software for injection well model and have mean error 2.204%. Meanwhile reservoir formation model has been validated using COMSOL Multiphysics software and have mean error 3.863%. The optimization of CO_2 EOR using Duelist Algorithm provide increasing the net profit 42.47% from 26,548.62 USD/day to 37,826.39 USD/day.

Keywords Enhanced oil recovery · CO_2 · Duelist algorithm

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Introduction

Oil and gas demand increase over the time due to increase in energy consumption especially in industrial and transportation sector. Although renewable and new energy have been utilized, oil and gas are still the major energy resources to fulfill the energy consumption demand. One of method to overcome the problem is enhanced oil recovery (EOR) (Widarsono 2013).

Enhanced oil recovery (EOR) is oil recovery by injecting of material and/or energy from outside the reservoir. EOR is a way to obtain residual oil that has not been lifted through the primary method. There are several EOR methods that have been developed and implemented in the oil field, including thermal recovery, chemical flooding, and solvent flooding (Mandadige et al. 2016; Donaldson et al. 1985). Each method has their advantages and disadvantages corresponding to the reservoir and oil characteristic.

The thermal recovery mechanism reduces oil viscosity. Chemical flooding (polymer) improves volumetric sweep by mobility reduction. While the miscible gas or solvent, reduces oil viscosity, development of miscible displacement and oil swelling (reduces oil density) (Lake 1989).

Injecting of miscible gas using CO_2 has some advantages compared to other methods, this method able to increase the production of 5–15% (Lake 1989) and CO_2 as the injected gas can reach the zones that have not been reached by waterflooding and reduce the trapped oil in the rock formations. EOR using the CO_2 injection method provides a positive impact to global warming conditions. By doing the CO_2 injection into the reservoir it has reduced the amount of CO_2 in the atmosphere where CO_2 gas is a pollutant that causes the greenhouse effect (Goeritno 2000; Aprilia Dwi Handayani 2011).

CO_2 injection is obtained from Carbon Capture and Storage (CCS) Unit (Bachu 2016). The operational costs consist of CO_2 purchase costs, CO_2 injecting costs depend on pressure, and flowrate of the injected CO_2 and costs of recycling CO_2 from the oil production (Cook 2012).

In this paper, the optimization of CO_2 EOR operation condition is performed using Duelist Algorithm (DA). The optimized variables are flowrate, pressure and temperature of injected CO_2. Optimization results are expected to increase the profitability of oil production.

Method

A. Determination of operating condition range of CO_2 flood operation and reservoir formation properties

The case study used in this paper is data from Morrow County, Ohio, USA. The reservoir depth is 1067 m, reservoir thickness is 10.4 m, reservoir temperature is 87 °F, minimum miscible pressure is 1087 psia, permeability is 18.1 mD, rock formation porosity is 0.07° and 41° API oil content are the parameter from Morrow County oilfield (Fukai and Mishra 2016). The reservoir shape is assumed cylindrical and isolated with distance from injection well to production well is 100 m. The applied operating condition include injection rate of CO_2 is 0.5 MMscfd with injection pressure is 1071 psia and temperature injection is 31 °C. The selection of this case study corresponds to the appropriate oil field for CO_2-EOR, which has a deep reservoir depth, low permeability and light oil (Lake 1989).

B. Problem formulation

Problem formulation consists of objective function and constrain of optimization. The objective function of the CO_2 EOR is to maximize oil production as well as increase profit. The amount of oil production is proportional to the injected CO_2. However, more CO_2 injected at certain pressure incur high cost. Cost of pumping and recycling the CO_2 also considered in the objective function. From the data mentioned before, profit can be calculated and represented as objective function as follows:

$$\text{Profit} = [\text{Revenue}] - [\text{Cost } CO_2] - [\text{Cost Recycling}] - [\text{Cost of pumping}] \quad (1)$$

where,

$$\text{Revenue} = [\text{Oil production}] \times [\text{Oil price}] \quad (2)$$

$$\text{Cost } CO_2 = [CO_2 \text{ gas flow rate}] \times [\text{Price per unit } CO_2] \quad (3)$$

$$\text{Cost recycling} = [\text{Volume recovery}] \times [\text{Price of recycling}] \quad (4)$$

$$\text{Cost of pumping} = [\text{Pump power}] \times [\text{Time operation}] \times [\text{Electricity price}] \quad (5)$$

C. Pressure drop modeling CO_2 EOR using Fanning, Darcy and Beggs-Brill methods

The operating condition of CO_2 EOR on the inlet and outlet of the reservoir change due to some mechanism processes inside reservoir and wellbores. The CO_2 EOR pressure drop modeling is divided into three modelling stages: injection well, reservoir formation and production well. Pressure drop on injection well is using Fanning equation, pressure drop on reservoir formation using Darcy equation and pressure drop on production well model using Beggs-Brill equation (Srichai 2006; Banete 2014; Beggs 1973). Properties of mixture between CO_2 and oil are obtained from HYSYS software. That properties used in pressure drop modeling on reservoir formation and production well. The models of pressure drop are validated using PIPESIM software for injection and production well model and using COMSOL Multiphysics software for reservoir formation model.

D. Estimation of addition oil recovery of CO_2 EOR

Estimation of addition oil recovery of CO_2 EOR using Koval method. Fractional flow of CO_2 and oil is affected by viscosity ratio between CO_2 and oil. The oil production rate is calculated through additional recovery, cumulative production and mass flow rate of CO_2 EOR. The amount of original oil in place is considered in the calculation of oil production rate (Rubin and McCoy 2006).

$$N_p = \frac{\alpha + (F_i)_{BT}}{1 + \alpha} \tag{6}$$

$$(F_i)_{bt} = \sqrt{\frac{0.9}{(M + 1.1)}} \tag{7}$$

$$\alpha = \frac{1.6}{K^{0.61}} \left[\frac{F_i - (F_i)_{bt}}{1 - (F_i)_{bt}} \right]^{\left(\frac{1.28}{K^{0.26}}\right)} \tag{8}$$

$$M = \frac{\mu_o}{\mu_s} \tag{9}$$

$$K = EHG \tag{10}$$

$$E = \left[0.78 + 0.22M^{1/4}\right]^4 \tag{11}$$

$$H = \left[\frac{V_{DP}}{(1 - V_{DP})^{0.2}} \right]^{10} \tag{12}$$

$$G = 0.565 \log\left(\frac{t_h}{t_v}\right) + 0.87 \tag{13}$$

$$\frac{t_h}{t_v} = 2.571 k_v A \frac{\Delta\rho}{q_{gross}\, \mu_s} \tag{14}$$

where:

N_p fraction of the displaceable residual oil in place recovered
$(F_i)_{bt}$ HCPV of CO_2 injected at the point at which CO_2 reaches the production wells
F_i HCPV of CO_2 injected
M Mobility ratio of the two fluids
K Koval factor
E Koval mobility factor
H Permeability heterogeneity factor
G gravity segregation factor
μ_o viscosity of the oil (kg/m s)
μ_s viscosity of CO_2 (kg/m s)
V_{DP} Dykstra-Parsons coefficient
k_v reservoir permeability in the vertical direction (m^2)
A Pattern Area (m^2)
q_{gross} gross injection rate of CO_2 (m^3/s).

E. **Optimization technique**

Objective function of CO_2 EOR can be obtain by determining the operating condition utilizing Duelist Algorithm (DA). The operating condition that optimized are mass flow rate, pressure and temperature of injected CO_2. The initialization for DA is

Table 1 Pressure drop parameter in injection and production well model (Dutt 2012)

Parameter	Value	Unit
Gravitation	9.8	m/s^2
Diameter of well	0.089	m
Reservoir depth	1067	m
Injection pressure	1071	psia
Mass flow rate	0.30443	kg/s
Injection temperature	31	°C
Wall thickness	0.005	m
Over-all heat transfer coefficient	2	Btu/h F ft^2

determine the initial parameters such as the number of chromosome 20 bit, population size 100, maximum generation 100, crossover probability 0.8, mutation probability 0.01 and elitism 0.95. Individual with the best fitness will be a solution to obtain the optimal objective function.

Result and Discussion

A. Pressure drop modeling in injection and production well

Pressure drop modeling in injection and production well are calculated based on parameter from Morrow County, Ohio, USA as the case study in this project. The parameters are on Table 1.

Pressure drop modeling in injection well using Fanning has been validated using PIPESIM software with mean error 2.204%. Pressure drop modeling in production well using Beggs-Brill equation also has been validated using PIPESIM with mean error 1.242%.

B. Pressure drop modeling in reservoir formation

Pressure drop modeling in reservoir formation using Darcy equation. Input pressure for this model is calculated from last segment output of injection well model. The calculation result of last segment in reservoir model becomes input for production well model. The reservoir formation properties are from Morro County, Ohio, USA on Table 2. Pressure drop modeling on the reservoir has been validated using COMSOL Multiphysics software with mean error 3.863%.

C. Calculation of additional recovery CO_2 EOR

Additional recovery is the increasing of oil production after CO_2 EOR. Based on the injection parameter before optimization, the gas flow rate is 0.5 MMscfd, then the oil production rate is 563.398 barrel per day. The crude oil price as the West

Table 2 Pressure drop parameter for reservoir formation model (Dutt 2012)

Parameter	Value	Unit
Injection-production well distance	100	m
Reservoir thickness	10.4	m
Permeability	18.1	mD
Porosity	0.07	–
Deg API	41	° API

Table 3 Calculation of net profit CO_2 injection operation

Parameter	Value	Unit
Revenue	28,482.613	USD/day
Cost of CO_2 purchase	1084.999	USD/day
Cost of CO_2 recycling	284.826	USD/day
Cost of pumping	564.165	USD/day
Net profit	26,548.622	USD/day

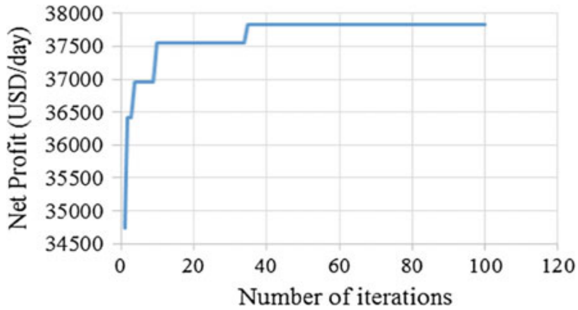

Fig. 1 The maximum objective function during iteration GA

Texas Intermediate (WTI) crude oil in Septembre 2017 of 50.556 USD/barrel, so the revenue based on Eq. (2) is 28,482.613 USD/day.

The CO_2 purchase cost unit price of 2.17 USD/Mcf, recycling cost unit price of 0.505 USD/Mcf and electricity price unit price 0.0974 USD/kWh. Based on Eqs. (3–5), the CO_2 purchase cost is 1084.999 USD/day, recycling cost is 284.826 USD/day and pumping cost is 564.165 USD/day. The calculation of net profit are shown in Table 3.

D. **Optimization of operating condition CO_2 EOR**

The objective function of this optimization is to obtain maximum net profit. The optimized variables are mass flow rate, pressure and temperature injection. The constraint is the production well head pressure more than 100 psia. The best fitness of net profit plot from each generations are shown in Fig. 1.

Optimization result show the net profit correspond to optimized variables are shown in Table 4.

Table 4 Calculation of net profit of CO_2 EOR after optimization

Parameter	Value	Unit
Revenue	40,623.933	USD/hari
Cost of CO_2 purchase	1551.829	USD/hari
Cost of CO_2 recycling	406.239	USD/hari
Cost of pumping	839.477	USD/hari
Net profit	37,826.387	USD/hari

Table 5 Optimized variable after optimization

Optimized variables	Value	Unit
Mass flow rate	0.4354	kg/s
Injection pressure	1100.205	Psi
Injection temperature	35.686	C

The optimized variables that used to obtain the optimal objective function are shown in Table 5.

Conclusion

Pressure drop of CO_2 EOR for injection well model is using Fanning equation, Darcy equation for reservoir formation and Beggs-Brill equation for production well. Mean error of pressure model in injection well to PIPESIM software is 2.204%, the mean error of pressure model in reservoir formation to COMSOL Multiphysics software is 3.863%. The net profit at Morrow County, Ohio, USA as the case study was increased 42.47% after optimized using DA from 26,548.622 USD/day to 37,826.387 USD/day.

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