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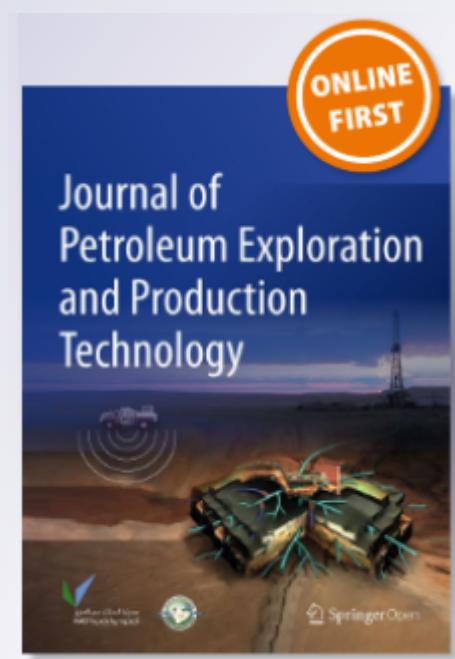Journal of
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Integrated simulation system of CO_2 gas injection application for enhanced oil recovery in the oil field

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Abstract

CO_2 gas injection is one of the recommended enhanced oil recovery (EOR) methods by injecting CO_2 through reservoir pores after the residual saturation is reached, since CO_2 dissolves easily in oil phase as confirmed by many other researchers in pertaining field studies. An integrated system is urgently required for assessing CO_2-EOR study, covering multi-disciplinary aspects as follows: geology, geophysics, reservoir, production, process and economic. Hence, those systems must be reliable in suggesting final decision for feasibility of CO_2-EOR operation program, applicable either for pilot scale or for full scale. This paper is proposing an integrated system evaluation, which has the following features: (1) estimate fraction of dissolved CO_2, (2) estimate viscosity reduction, (3) estimate future oil productivity index resulted, (4) forecast incremental oil production, (5) estimate surface facilities equipment design, (6) evaluate economical aspects and (7) generate final decision for feasibility of CO_2-EOR operation program. Finally, as the main objective of this program, those systems will present a picture of essential reason why we need to promote or reject CO_2-EOR plan program, and also some recommendations will be presented in case the CO_2-EOR plan does not perform as expected.

Keywords CO_2 gas injection · Enhanced oil recovery (EOR) · Integrated system

Introduction

Indonesia approximately has 998 million BOE (Barrel Oil Equivalent) of national energy demand, relying on crude oil as the main energy source (MEMRRI 2017). Furthermore, 90% of national oil production comes from depleted oil fields. If we persist in this situation without doing any exploration and discoveries, 3.6 billion of proven Indonesia's oil reserve will completely drained within the next 11 years (SKK Migas 2016).

Pertamina as an Indonesia's national oil and gas company has about 110 Tscf of natural gas sources, associated with large amount of CO_2 content (Suarsana 2010). CO_2 could reduce heating value and contribute to global warming this situation can lead to detrimental issues in economic and environmental aspect, but from another perspective we can turn these issues into new opportunity to enhance oil production by employing CO_2-EOR. To raise that program, it is necessary to initiate a conceptual feasibility study of CO_2-EOR, engaging essential aspect, such as thermodynamic equilibrium of CO_2 dissolved in oil phase, oil recovery gain due to dissolved CO_2, CO_2 transport and CO_2 natural gas purification facilities.

Some previous research has been greatly conducted by some researchers including feasibility study (LPPM UPN 2011; Muslim 2013; Chae and Lee 2015; Lee 2015; Abdurrahman et al. 2017), technical research (Suarsana. 2010; Rostami et al. 2017) and laboratory experiments (Abdassah et al. 2000). From those studies, we can derive some essential factors of CO_2-EOR fruitfulness, such as decreased oil viscosity (Abdassah et al. 2010; Rostami et al. 2017; Miller and Jones 1981), oil expansion (Emera and Sarma 2006), oil extraction and evaporation (Abdassah 2010; Leach and

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Yellig 1981; Yellig 1982) and solution gas drive (Holm and Josendal 1974; Sohrabi and Emadi 2012).

This paper is tackling an integrated system of some essential aspects in CO_2-EOR process, encompassing many aspects as follows: geophysics, geological, reservoir and production (GGRP) data properties, the maximum CO_2 dissolved at certain pressure and injection rates to increase oil recovery, purification facilities and economics, which can be relied upon as an application to provide simple, precise and fast screening for CO_2-EOR.

Research methodology

The methodology derived from essential aspects in CO_2-EOR as mentioned earlier, begins with GGRP data properties followed by rate and injection pressure of CO_2 design. These data will govern oil viscosity potential which affects oil recovery gain and surface facilities design. Consequently, these two outputs will govern economic evaluation used for final decision. All of these methods are presented in Fig. 1.

Geology, geophysics, reservoir, and production data (GGRP data)

As initial requisite data, geology, geophysics, reservoir and production detail data are as follows:

a. Geology and geophysics data

- Map area, topography and geology
- Geophysical survey, contour map and isopach map (formation thickness, porosity, permeability)

b. Reservoir data

- Rock properties (porosity, permeability, saturation, etc.)
- Fluid properties (specific gravity, viscosity, oil formation volume factor, etc.)

c. Production data

Flowing well pressure (Pwf), production rate, inflow performance relationship (IPR), tubing performance relationship (TPR), bottom-hole temperature (BHT)

Oil recovery due to oil viscosity potential

To compute oil recovery gain, we use five governing equations which are solved sequentially, and detail explanations are presented below:

1. CO_2 mass equilibrium is modeled under steady-state condition, determined by CO_2 injection rate.

$$y_{CO_2}\big|_t = y_{CO_2}\big|_{t=0} - \frac{B_o \rho_o s_o \varepsilon}{Q_{inj} t}\left(x_{CO_2}\big|_t - x\big|_{t=0} \right) \qquad (1)$$

2. CO_2 mass equilibrium considered by thermodynamic aspects, where the fugacity of each phase is a function of Peng–Robinson's (EOS) equation of state (EOS). By engaging EOS, this simulation can compute CO_2 injection scenario whether in liquid or in gas phase. In cases of injected CO_2 in undersaturated liquid phase, fugacity is ≈ 1.

$$x_{CO_2}^{oil} \emptyset_{CO_2}^{oil}(P, T) = y_{CO_2}^{gas} \emptyset_{CO_2}^{gas}(P, T) \qquad (2)$$

Fig. 1 Flowchart of CO_2-EOR study
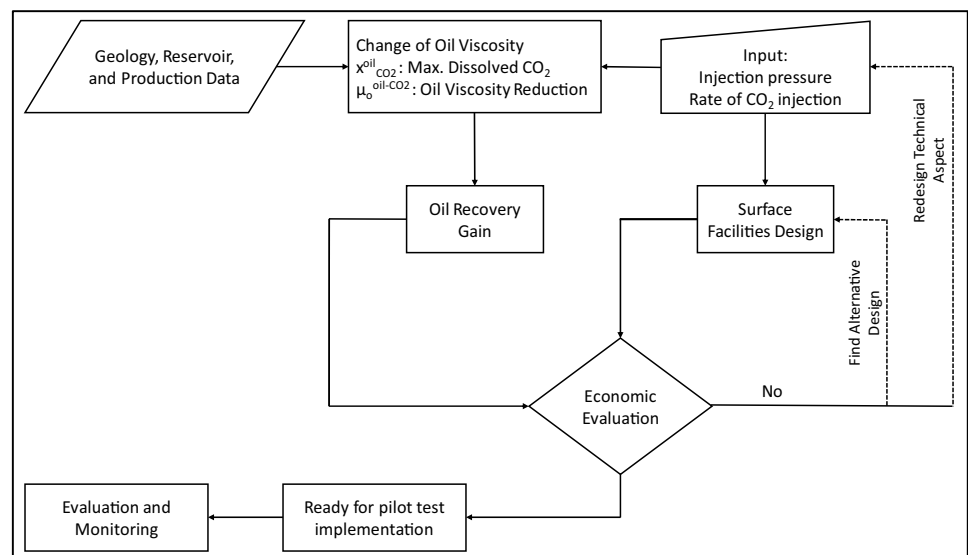
3. As the amount of dissolved CO_2 has increased, chemical structure of oil will be changed, this process could lower oil viscosity, and the change of viscosity is described by the proposed correlation of Barclay and Mishra (2016):

$$\mu_{\text{oil-}CO_2} = \mu_{\text{oil}}(1 + 0.01113T - 1.78210)x^{\text{oil}}_{CO_2} \qquad (3)$$

4. Since oil viscosity has reduced, mobility ratio also reduced, meaning oil production will increase as oil will move easier in the pore space. The oil production and oil viscosity relation is described by Vogel inflow performance relationship (IPR) equation:

$$Q_o = J(\bar{p}_r - p_{\text{wf}}) + \frac{Jp_b}{1.8}\left(1 - 0.2\left(\frac{p_{\text{wf}}}{p_b}\right) + 0.8\left(\frac{p_{\text{wf}}}{p_b}\right)^2\right) \qquad (4)$$

where

$$J = 0.00708\,\text{kh}\left(\mu_o B_o\left(\ln\left(\frac{r_e}{r_w}\right) - 0.5\right)\right)^{-1} \qquad (5)$$

5. Percent of the amount of oil produced is described by the equation below:

$$\text{RF} = \frac{s_{\text{oi}} - s_o}{s_o} \qquad (6)$$

where oil recovery gain is derived from the mass balance equation in an unsteady state, with oil saturation (s_o) is dependent variable, and time (t) is independent variable.

$$s_o = s_{\text{oi}} - \frac{Qt}{\varepsilon V_R B_o} \qquad (7)$$

There is two alternatives design of CO_2 purification facilities, as follows: distillation and absorption method. Distillation column is computed by three main equations: mass balance, phase balance and heat balance. These three equations are solved using a numerical program or a process simulation program, whereas in the absorption method, CO_2 separation mechanism begins with: natural gas entering through the bottom of the absorption column, while absorbent liquid enters through the top of the tower, and the gas and liquid will contact each other, where the absorbent liquid will absorb the CO_2, and liquid absorbent is mainly comprised of alkylamines, such as diethanolamine (DEA), monoethanolamine (MEA) and methyldiethanolamine (MDEA) (Miller et al. 1978; Gary et al. 1984; Kohl and Richard 1997; LPPM 2011). Estimation of absorber tower is calculated based on two concepts, that is concept of phase equilibrium between gas and liquid, analogously as Eq. (2) and also the concept of mass transfer between gas and liquid.

Results and discussion

The integration of CO_2 gas injection simulation was started from building flowchart as shown in Fig. 1, begun with GGRP data and operating pressure, these data will generate estimation of oil recovery gain and surface facilities design, this information could be our guidance to evaluate whether this project is feasible or not, data from GGRP give essential information such as reservoir size and fluid properties, these data are delivered into three following equations, as follows: equation of mass balance under steady-state condition, CO_2 phase equilibrium by Peng–Robinson equation of state and change of oil viscosity.

We are attempting to simulate a CO_2 flood by injecting CO_2 mixture in gas phase into reservoir with total targeted drainage volume as much as 0.5 MMCF, total injected gas is 31 MMSCFD flowing through many injection well, and injection pressure was varying from 600 up to 2400 psig. The reservoir and injection data are presented in Tables 1 and 2.

The simulation starts from computing the effects of CO_2 concentration in oil phase as a function of the rate of CO_2 injection. As a result, as presented in Fig. 2, we can see the intersection point between the CO_2-oil absorption line due to the CO_2 injection process (Eq. 1) and the inter-phase equilibrium line computed from EOS (Eq. 2). The point of intersection is the optimum CO_2-oil equilibrium point.

As a result, 0.027 CO_2 fraction in crude oil phase was obtained at 600 psig of CO_2 injection pressure and 1800 days cumulative, dissolved CO_2 will reduce oil viscosity with respect to cumulative days injection, followed by the alteration of well IPR, and then, the oil recovery gain will be estimated as shown in Fig. 3 through Fig. 5 and Table 4, respectively.

Table 2 Injection fluid properties data

Q_{inj} (MMSCFD)	Pressure (psig)	Temperature (°F)	% mole CO_2
100	600	180	0.85

Table 1 Reservoir properties data

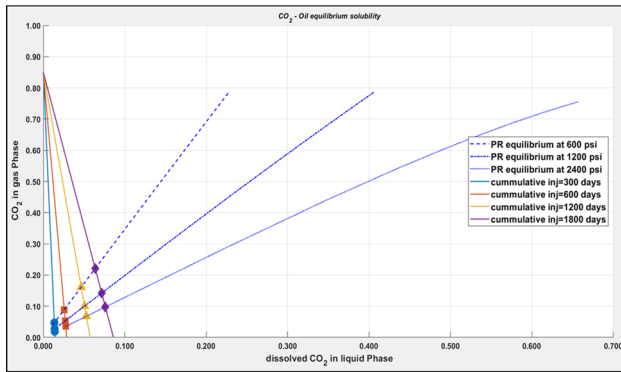| Vol. reservoir drainage target (cuft)	Pwf (psig)	ϕ	s_o	°API	μ_o (Cp)	B_o (RB/STB)	BHT (°F)	Oil prod. (BOPD)
500.000	200	0.11	0.20	33.80	2.45	1.2	180	300

Fig. 2 Graph of the CO_2 equilibrium in the gas-oil phase. Note: filled circle = cumulative injection day 300, filled square = cumulative injection day 600, filled triangle = cumulative injection day 1200, filled diamond = cumulative injection day 1800, straight line = phase equilibrium at P = 600 psig, straight with dotted line = phase equilibrium at P = 1200 psig, dotted line = phase equilibrium at P = 2400 psig
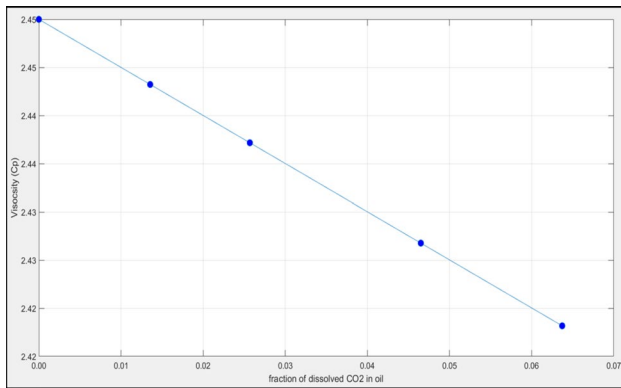

Fig. 3 Effect of oil viscosity due to fraction of dissolved CO_2 and cumulative day of injection

In Fig. 3, we can see that as higher cumulative days of injection we got higher CO_2, this happened due to the accumulation of CO_2 in the oil phase, for example at a pressure of 600 psig and the cumulative 300 days, we obtained an equilibrium of CO_2 fraction in oil (xCO_2) as much as 0.01 until the cumulative 1800 days. Similarly, in other simulations we computed higher pressure and we got higher value of xCO_2.

Then, the simulation is continued by entering parameters in the target field, and the target field parameter data can be seen in Tables 1 and 2. The simulation of the changes in oil viscosity due to CO_2 levels in oil is presented in Fig. 3; it shows that the greater the CO_2 content dissolved in oil will lower viscosity, and the longer duration of imbibition also affects the oil viscosity as shown in Fig. 4.
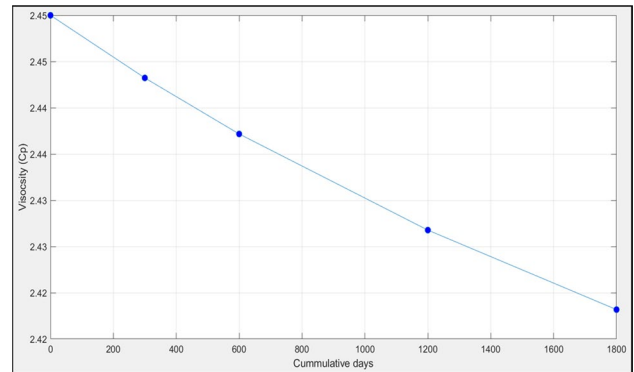
Fig. 4 Effect of oil viscosity vs cumulative days of injection
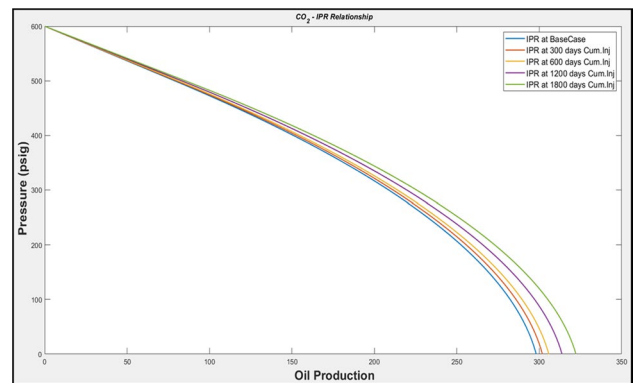
Fig. 5 Graph of future inflow performance relationship (IPR)

Table 3 Comparison of daily oil production within conventional method and CO_2 flood method

No	Daily oil prod (BOPD)		Cummulative days of injection	Gain (%)
	Without CO_2 flood	CO_2 flood method		
1	252	252	0	0.0
2	252	256	300	1.5
3	252	260	600	3.1
4	252	266	1200	6.7
5	252	273	1800	8.0

Simulation of inflow performance relationship improvement and cumulative oil production due to CO_2 fraction in oil

In this sub-section, we computed inflow performance relationship values at various viscosity values due to accumulation of dissolved CO_2 during injection process. In Fig. 5, it can be seen that the injection pressure at

600 psig gives an increase of IPR in every cumulative day of injection, which affects cumulative oil production (Eqs. 6 and 7). From Fig. 5 and Table 3, it shows that in the cumulative 300 days, CO_2 injection method takes the lead in cumulative oil production compared to conventional method.

Estimated cost of CO_2 purification facilities

In this section we will discuss estimation cost of CO_2 purification, with baseline 31 MMSCFD of gas feed. By computing in commercial process simulation software we got results as presented in Table 4, we can see that the cost of equipment for the cryogenic distillation method is about $ 9.5 million, with 86% purity of CO_2 gas product.

CO_2 purification facilities are available in two options: cryogenic distillation facilities and contactor amine facilities. Cryogenic distillation is recovering CO_2 by separating mixture based on boiling point differences, as shown in Fig. 6. Cryogenic distillation facilities consist of two compressors, two columns distillation and tank. Gas compressor is inflating gas pressure, gas flowing into demethanizer

contactor separating gas from light hydrocarbon mixture (mainly methane), top product is send to DHU and bottom product is flowing into CO_2-column, top product (mainly CO_2) is flowing into injection compressor, and bottom product or condensate product is sent to liquid tank. Contactor amine facilities are to recover CO_2 by absorbing CO_2 through DEA/MDEA, as shown in Fig. 7. Amine facilities have three main units for processing: compressor, DEA contactor, DEA recovery column. The compressor is used to increase the pressure, then the gas is flowing into DEA contactor to dehydrated hydrocarbon gas, the bottom product of DEA contactor is flow into DEA recovery column to clean up DEA, and thus, it can be recycled into DEA contactor. Total investment for facilities is available in three options: $19.5 M for MDEA contactor, $19 M for DEA contactor and $9.5 M for cryogenic distillation as described in Table 4, whereas the process flow diagram (PFD) of purification facility can be seen in Figs. 6 and 7, respectively.

Table 4 Simulation results of CO_2 gas purification by various methods

Feed rate (MMSCFD/day)	% mol CO_2 feed	Sweet gas (m³/day)	% CO_2 sweet gas	Rate of CO_2 product	% mol of CO_2 at CO_2 product	Investment cost (million USD)
Contactor MDEA						
31	29	19	5	12	68	19.5
Contactor DEA						
31	29	19	5	12	67	19
Cryogenic distillation						
31	29	20	3.5	20	86	9.5

Fig. 6 PFD of cryogenic distillation facilities

Fig. 7 PFD of contactor amine facilities

Conclusion

Based on the results of the analysis and discussion above, it can be concluded as follows:

1. Evaluation of CO_2-EOR feasibility can be obtained from integration of the following aspects:
a. GGRP data properties, maximum CO_2 dissolved and CO_2 injection rates can estimate oil recovery gain.
b. The needs of CO_2 supply and oil recovery gain will affect design of surface facilities.
c. Oil recovery gain and the need of surface facilities are used for economic consideration.
2. The integration of GGRP aspects is able to provide an overview of the feasibility evaluation of CO_2-EOR, quickly, simply and integrated.
3. The simulation study conducted is very useful as a guide before starting the CO_2-EOR study in more detail using reservoir models and EOS pressure volume temperature (PVT) regression analysis for CO_2-hydrocarbons.

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