Determination of Effective Parameters of Gas Injection in Naturally Fractured Reservoirs by Combination of Reservoir Simulation and Design of Experiment Techniques

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Abstract. Screening analysis is a useful guideline which helps us with proper field selection for different enhanced oil recovery processes. In this work, reservoir simulation is combined with experimental design to estimate main effects and possible interactions of reservoir rock and fluid properties on performance of different gas injection processes in naturally fractured reservoirs (NFRs). Studied parameters include reservoir thickness (h), oil viscosity (µo), pore size distribution (λ), horizontal permeability (Kh), storage capacity (ω), reservoir dip, critical water saturation (Swc) and threshold capillary pressure (pct). The recovery factors of different simulation designs are analyzed by use of fractional factorial design (FFD) approach. Finally, the statistical significance of results are evaluated by hypothesis testing and ANOVA, and presented by Pareto and tornado plots. Main effect analysis showed that effective parameters are ordered with respect to their importance as follows: For Methane and nitrogen injection: Kh, dip, Swc, ω, h, µo and λ; threshold capillary pressure showed a minor effect on recovery factor. For Carbon dioxide injection: µo, dip, Swc, ω, h and Kh; Pore size distribution (λ) and threshold pressure were not shown to be statistically significant in this process. Likeness of main effects and parameter interactions for methane and nitrogen injection prove the similarity of dominant mechanisms and characteristics of these processes compared to CO2 injection which seems almost different.

1. Introduction
Gas injection improves the oil recovery with maintaining the reservoir pressure, displacing oil and vaporizing the intermediate fraction of the reservoir fluid. Screening criteria for different enhanced oil recovery techniques have been comprehensively studied in the literature [1-3]. Manrique et al. (2007) reviewed conventional screening for different EOR methods in the carbonate oil reservoirs [4]. Conventional and advanced screening methods for evaluating the applicability of EOR processes in a particular field were discussed by Manrique and Pereira (2007), Alvarado et al. (2002) and Alkafeef and Zaid (2007) [5-7]. Vanegas Prada and Cunha (2008) used experimental design techniques to develop a response surface correlation to estimate SAGD performance [8]. Amudo et al. (2009) proved the pains and gains of experimental design and response surface application in reservoir simulation studies and showed that improper selection in the range of parameters can cause the Pareto chart to be interpreted
incorrectly in screening process [9]. Moradi et al. (2010) and Fereidooni et al. (2012) investigated dominant parameters in gas injection via reservoir simulation studies [10, 11]. Bengar al. (2017) and Mohsenatabar and Moradi (2018) applied combination of fractional factorial design and reservoir simulation to investigate the important factors affecting performance of polymer flooding and ASP processes, respectively [12, 13].

In this paper, the influential parameters of different gas injection processes (including methane, nitrogen and carbon dioxide) in fractured reservoirs are investigated via combination of experimental design and reservoir simulation studies. Afterwards, statistical analysis (i.e. hypothesis testing) is applied for further analysis of main effects and interactions of parameters and increase the reliability of screening results.

2. Theory and Method

2.1. Design of Experiments (DOE)
Design of experiments is a series of tests in which purposeful changes are made to the input variables of a system or process and the effects on response variables are measured. DOE is applicable to both physical processes and computer simulation models. Experimental design is an effective tool for maximizing the amount of information gained from a study while minimizing the amount of data to be collected. Factorial experimental designs investigate the effects of many different factors by varying them simultaneously instead of changing only one factor at a time. Factorial designs allow estimation of the sensitivity to each factor and also to the combined effect of two or more factors [14].

2.1.1. Statistical Analysis of main effects
The independent effect of each parameter on increasing/decreasing the recovery factor is explained with the concept of main effect. Actually the main effect explains the mean value effect of each parameter as changing from its minimum to maximum. Main effect for any factor can be determined by 

\[
\text{Main effect} = (\text{Average RF when the parameter takes maximum level}) - (\text{Average RF when the parameter takes minimum level})
\]  

2.1.2. Determination and statistical analysis of interactions
Parameter interaction means, the effect of each parameter is different in minimum or maximum value of other parameters. Interaction effect could exist between two, three and more parameters. Usually with increasing the number of parameters that exist in the interaction between parameters, these effects are reduced. In this paper we study only the interaction effect of two parameters. Considerable variation in a set of effects may be an evidence for two factor interactions. This occurs when a parameter increases or reduces the effect of other ones. Resolution of experimental design plays a key role in successfully calculation of interactions. For example, designs with resolution III are usually inappropriate to estimate two factor interactions because many of them are confounded with main effects. Based on sparsity of effects (NIST/SEMATECH,2006), it is assumed that the higher order interactions are small compared to lower order ones and the higher order interactions are ignored [15,16].

2.2. Model Specification and Parameters
A compositional model was constructed by CMG/GEM to investigate the parameters that would affect the performance of gas injection in a quarter sector of a five-spot pattern in a fractured reservoir as shown in figure 1. The sector model dimensions are 2000 ft in length and 1000 ft in width and consists of three layers. Injection well is controlled by a constant bottom hole pressure constraint, and well production continues at a constant production rate until it reaches a minimum value of 20 STB/day.
Figure 1. Schematic of sector model

The fractional factorial approach was applied to design the simulation runs for the considered parameters (absolute horizontal permeability ($k_h$), reservoir thickness ($h$), dip angle, connate water saturation ($s_{wc}$), threshold capillary pressure ($p_{ct}$), oil type, pore-size distribution index ($\lambda$) and fracture storage capacity ($\omega$)).

The equations to generate relative permeability and capillary pressure curves are as follows:

$$k_{r,wt} = (s_{wt}^*)^{2+\lambda}$$  \hfill (2)

$$k_{r,nwt} = (1 - s_{wt}^*)^2[1 - (s_{wt}^*)^{2+\lambda}]$$  \hfill (3)

$$p_c = p_{ct} s_{wt}^* \frac{\lambda}{1+\lambda}$$  \hfill (4)

where

$$S_w^* = \frac{s_w - s_{wc}}{1 - s_{wc}}$$ \hfill (5)

$K_{r,nwt}$, $K_{r,wt}$, $\lambda$, $P_c$ and $P_{ct}$ account for relative permeability of the non-wetting phase, relative permeability of the wetting-phase, pore size distribution index, capillary pressure and threshold capillary pressure, respectively. The fracture storage capacity ($\omega$) is defined as:

$$\omega = \frac{\phi_{ct} f}{\phi_{ct} f + m}$$ \hfill (6)

The studied parameters and a summary of design table including the recovery factor results for methane, nitrogen and carbon dioxide gas injection are presented in Tables 1 and 2.

Table 1. Minimum and maximum values of parameters

| Parameter                        | Unit   | Min(-1) | Max(+1) |
|----------------------------------|--------|---------|---------|
| Absolute horizontal permeability | md     | 35      | 500     |
| Reservoir thickness              | ft     | 180     | 1000    |
| Dip angle                        | degree | 5       | 40      |
| Connate water saturation         | fraction | 0.1    | 0.4     |
| Threshold pressure               | psi    | 0.75    | 2       |
| Type of oil                      | dimensionless | light | heavy   |
| Pore size distribution           | dimensionless | 1.5    | 6       |
Table 2. Matrix of Runs for different gases injection

| Run | Dip  | Thickness | $\omega$ | Type of oil | $K_h$ | $S_{wc}$ | $\lambda$ | $P_{oth}$ | RF (N$_2$) | RF (CH$_4$) | RF (CO$_2$) |
|-----|------|-----------|--------|------------|------|--------|--------|--------|----------|-----------|-----------|
| 1   | 40   | 1000      | 0.6    | heavy      | 500  | 0.4    | 6      | 2      | 60.2389  | 71.9514   | 74.7623   |
| 2   | 5    | 1000      | 0.6    | heavy      | 500  | 0.4    | 1.5    | 2      | 50.5629  | 64.3556   | 71.6773   |
| 3   | 5    | 1000      | 0.6    | light      | 500  | 0.4    | 6      | 0.75   | 50.9517  | 68        | 79.9284   |
| 4   | 40   | 1000      | 0.6    | light      | 500  | 0.4    | 1.5    | 0.75   | 52.1623  | 68        | 79.3657   |
| 5   | 5    | 1000      | 0.6    | light      | 500  | 0.1    | 6      | 2      | 64.151   | 72        | 84.2017   |
| 6   | 40   | 1000      | 0.6    | light      | 500  | 0.1    | 1.5    | 2      | 66.1529  | 73.1503   | 80.2443   |
| 7   | 5    | 180       | 0.1    | light      | 35   | 0.4    | 1.5    | 0.75   | 42.9177  | 46.1813   | 83.7334   |
| 8   | 40   | 180       | 0.1    | light      | 35   | 0.1    | 6      | 2      | 64.211   | 69.3154   | 86.9115   |
| 9   | 5    | 180       | 0.1    | light      | 35   | 0.1    | 1.5    | 2      | 46.9919  | 46.9156   | 82.2115   |
| 10  | 5    | 180       | 0.1    | heavy      | 35   | 0.1    | 6      | 0.75   | 38.2156  | 38.9659   | 69.5619   |
| 11  | 40   | 180       | 0.1    | heavy      | 35   | 0.1    | 1.5    | 0.75   | 51.9188  | 62.9166   | 74.9177   |

3. Results and Discussions

Main effect of each parameter is defined as the difference between the average RF when the parameter takes maximum level and the average RF when the parameter takes minimum level. Parameter interactions consider the fact that the effect of each parameter is different in minimum or maximum value of other parameters. In this paper, two-parameter interaction effects are considered.

Statistical inference test was conducted on calculated main effects and interactions to verify their statistical significance by using hypothesis testing (P-values less than 0.0001 were considered significant). Main effects and statistically significant parameter interactions for different injected gases are shown in Tables 3 and 4.

Table 3. Main effect analysis

| Factor | Nitrogen Main effect | p-value | Methane Main effect | p-value | Carbon Dioxide Main effect | p-value |
|--------|----------------------|---------|---------------------|---------|---------------------------|---------|
| dip    | 10                   | <0.0001 | 10.83               | <0.0001 | 2.87                      | <0.0001 |
| $H$    | 4.36                 | <0.0001 | 6.66                | <0.0001 | 1.46                      | <0.0001 |
| $\omega$ | -6.34                | <0.0001 | -2.69               | <0.0001 | -2.16                     | <0.0001 |
| Type of oil | -4.19            | <0.0001 | -1.74               | <0.0001 | -9.78                     | <0.0001 |
| $k_h$ | 11.86                | <0.0001 | 11.97               | <0.0001 | 1.30                      | <0.0001 |
| $s_{wc}$ | -6.54               | <0.0001 | -3.54               | <0.0001 | -2.77                     | <0.0001 |
| $\lambda$ | 3.67               | <0.0001 | 1.41                | <0.0001 | 0.63                      | 0.0090  |
| $P_{oth}$ | 1.41                | 0.0131 | 0.70                | 0.0326  | -0.66                     | 0.0067  |

Results show that the most important parameters in methane and nitrogen injection are horizontal permeability, dip angle and reservoir thickness; i.e. thick high permeability dipped reservoirs will show better gas injection performance. In carbon dioxide injection, however, the most important parameter is type of oil; light oil reservoirs have very low IFT with CO$_2$, showing near miscible or miscible displacement characteristics which results in higher recovery factors compared to immiscible displacement mechanism of methane and Nitrogen. Fracture storage capacity has negative effect on gas injection performance since it causes early breakthrough of injected gas in highly fractured reservoirs [17]. Effect of threshold capillary pressure and pore size distribution index are minor compared to other parameters. Visual comparison of main effects is presented in Figure 2.
Table 4. Statistical analysis of two-parameter interactions

| Factor | Nitrogen Interaction effect | P-value | Methane Interaction effect | P-value | Carbon Dioxide Interaction effect | P-value |
|--------|---------------------------|---------|---------------------------|---------|----------------------------------|---------|
| Dip * h | -0.59 | 0.2782 | -4.29 | <0.0001 | -1.47 | <0.0001 |
| Dip * wo | -0.44 | 0.4162 | 0.16 | 0.6125 | -0.044 | 0.8460 |
| Dip * type of oil | 1.38 | 0.0151 | 0.71 | 0.0285 | 2.44 | <0.0001 |
| Dip * k_h | -2.40 | 0.0001 | -4.92 | <0.0001 | -0.62 | 0.0103 |
| Dip * S_wc | -2.08 | 0.0005 | -1.14 | 0.0009 | -0.32 | 0.1718 |
| Dip * λ | 1.34 | 0.0181 | 1.26 | 0.0003 | 0.77 | 0.0018 |
| Dip * p_ct | 0.49 | 0.3653 | 0.24 | 0.4532 | -0.62 | 0.0096 |
| Dip * S_wc | -0.80 | 0.1484 | -0.35 | 0.2730 | 0.038 | 0.8688 |
| Dip * p_ct | -0.37 | 0.5010 | -0.99 | 0.0032 | 0.48 | 0.0421 |
| wo * type of oil | -0.11 | 0.8398 | 0.058 | 0.8532 | 0.014 | 0.9509 |
| wo * k_h | 0.16 | 0.7222 | -0.10 | 0.7437 | 0.14 | 0.5434 |
| wo * S_wc | 0.31 | 0.5647 | 0.098 | 0.7546 | 0.078 | 0.7306 |
| wo * λ | -0.076 | 0.8879 | 0.086 | 0.7838 | 0.11 | 0.6247 |
| wo * p_ct | -0.074 | 0.8918 | -0.036 | 0.9088 | 0.058 | 0.7985 |
| Type of oil * k_h | 2.25 | 0.0002 | 1.51 | <0.0001 | 4.03 | <0.0001 |
| Type of oil * S_wc | 2.40 | 0.0001 | 0.26 | 0.4046 | -1.32 | <0.0001 |
| Type of oil * p_ct | -0.46 | 0.3983 | 0.95 | 0.0046 | 0.078 | 0.7321 |
| k_h * S_wc | -2.67 | <0.0001 | -1.84 | <0.0001 | -1.43 | <0.0001 |
| k_h * λ | -0.55 | 0.3126 | 0.52 | 0.1053 | -0.15 | 0.5226 |
| k_h * p_ct | 0.66 | 0.2265 | 0.38 | 0.2355 | 0.054 | 0.8109 |
| S_wc * λ | -1.86 | 0.0016 | 0.59 | 0.0672 | -0.93 | 0.0003 |
| S_wc * p_ct | 0.37 | 0.4928 | -1.32 | 0.0002 | -0.23 | 0.3136 |
| λ * p_ct | 1.33 | 0.0190 | -4.29 | <0.0001 | 0.15 | 0.5098 |

Figure 2. Visual comparison of main effects in different gas injection processes.
Among two-parameter interactions, interactions of dip*kh, dip*Swc, h*kh, kh*Swc, type of oil*kh and type of oil*Swc for nitrogen injection, dip*h, dip*kh, dip*Swc, dip*, h*kh, kh*Swc, type of oil*kh and Swc*Pct for methane injection and dip*h, dip*type of oil, h*kh, type of oil*kh and type of oil*Swc, kh*Swc and Swc*λ. for CO2 injection are statistically significant and must be considered beside main effects in generating a correlation to estimate recovery factor of different gas injection processes. Likeness of main effects and parameter interactions for methane and nitrogen injection prove the similarity of dominant mechanisms and characteristics of these processes compared to CO2 injection which seems almost different.

4. Conclusions
According to this study, the following conclusions were made:

➢ The most important parameters in methane and nitrogen injection include horizontal permeability, reservoir thickness and dip angle; i.e. thick high permeability dipped reservoirs will show better gas injection performance.

➢ For carbon dioxide injection, the most important parameter is type of oil; light oil reservoirs have very low IFT with CO2, showing near miscible or miscible displacement characteristics which results in higher recovery factors.

➢ Fracture storage capacity has negative effect on gas injection performance since it causes early breakthrough of injected gas in highly fractured reservoirs.

➢ A correlation for recovery factor of different gas injection processes can be generated according to determined main effects and statistically significant interactions. This correlation creates an engineering approach in reservoir screening for gas injection process.

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