Sensitivity Analysis on Effective Parameters on Water Alternative Gas (WAG) for Enhanced Oil Recovery(EOR)

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Abstract

Enhanced oil recovery (EOR) methods are employed for increasing oil recovery after natural production of the reservoir. Each EOR process has limitation for applying in reservoirs due to rock and fluid condition. In water alternating gas (WAG) flooding, many parameters such as reservoir thickness, horizontal permeability, connate water saturation effect on oil recovery factor. In this study, main parameters that effect on WAG oil recovery were discussed using fraction factorial design and simulation. The CMG-GEM was used for simulation study. The Minitab statistical experimental design software was used for stochastic analysis. The results show reservoir thickness, connate water saturation, and the interaction of two parameters reservoir dip angle and horizontal permeability had main effect on oil recovery factor. Finally, a regression model based on the effective parameters was obtained. This regression model can be used to estimate the oil recovery during WAG flooding. According to the results of this study, the performance of WAG process in different candidate reservoirs can be predicted and one can rank the reservoirs to select the one with maximum recovery factor for further detailed reservoir and pilot studies.

Keywords: EOR, Water Alternative Gas, WAG, CMG, GEM, Optimization.

1. Introduction

Oil production life of a reservoir includes three stages. The first, primary production; in this stage oil production comes from natural pressure depletion. At the end of this stage, large amount of oil remains as residual oil. The second stage, secondary production; in this stage external fluid such as gas and water are injected into gas cap and aquifer for pressure maintains. At the end of this stage large amount of oil isn't produced still. The third stage, tertiary oil recovery; in this stage EOR methods are employed to produce residual oil [1]. EOR methods including four main classes: thermal, chemical, miscible gas, and microbial [2]. A thermal process is applying in reservoirs that contain heavy oil such as tar sand. Chemical methods include any process to decrease interfacial tension (IFT) of oil and water, such as surfactant and mobility control such polymer flooding or the mixture of them to increase oil recovery. In miscible flooding, gas such CO_2 is employed to recover oil by sweeping the oil [3]. In the microbial process, in-situ microbe reacts with carbon source and creates an in-situ surfactant [4]. As shown in figure 1, world EOR projects usually have been focused on thermal flooding [5].

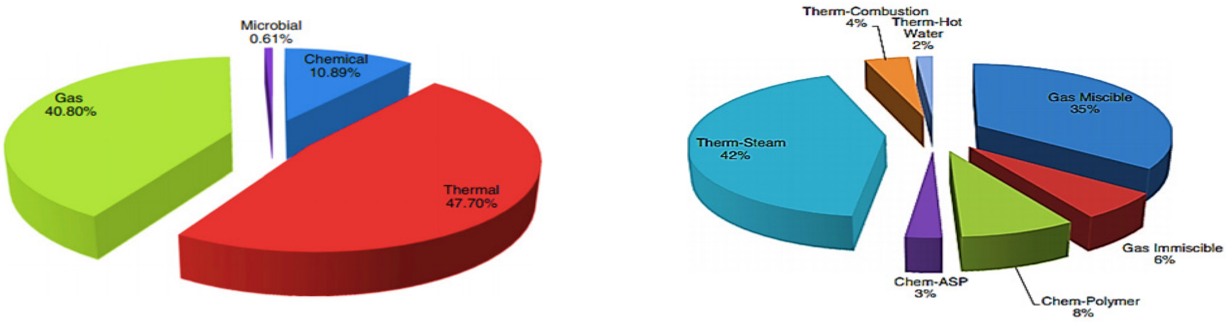

Fig 1. EOR process in world [5].

Gas miscible and immiscible flooding is the second interest of the world EOR project. The CO_2 flooding as the immiscible EOR process is used to increase oil recovery by sweeping the oil toward production well. In some case, CO_2 leaves the porous media due to fingering phenomena [6]. This phenomenon occurs in the reservoir with heterogeneity such as fracture. Therefore, water is employed to increase the efficiency of CO_2 flooding by increasing sweep efficiency in microscopical scale. This process is called water alternative gas flooding or WAG [7]. More than, WAG process is used to decrease the volume of the desirable costly CO_2 [8]. The WAG review shows that this procedure has been applied to rocks from very low permeability chalk up to the high permeability sandstone. Most of the applied processes were miscible. The miscibility issue is generally based on the gas availability but is mainly reported as an economic consideration and the extent of reservoir depressurization required for process application [9]. The main concerns for WAG are rock and fluid characteristics, reservoir characteristics and heterogeneity, the composition of injection gas, injection pattern, and WAG ratio [10]. Therefore, it is important to study the behavior of affecting parameters on WAG efficiency.

According to previous studies on the WAG process, the parameters were considered to examine its effect on WAG performance, including injection pressure, injection rate, well pattern, and slug size [11-14]. In this study, the author seeks to identify the effect of reservoir properties on the WAG. In addition, the effect of two different injection gases (CO_2 and N_2) will also be involved as another parameter. In the present work, main parameters including reservoir temperature, reservoir thickness, horizontal permeability, reservoir dip angle, connate water saturation, and nitrogen (N_2) content of injected gas are employed to determine the effect of them on oil recovery factor (as a response parameter) using experimental design and numerical simulation.

For simulation case, CMG-GEM is considered for reservoir sector simulation. Also, the Minitab is used for experimental design and statistical analysis.

2. Experimental Design and Numerical Simulation

Experimental design methods have been widely used in all kinds of industrial experiments since being developed for physical agricultural experiments, almost 50 years ago [15]. A common experimental design is one with all input factors set at two levels. These levels are called `high' and `low' or "+1" and "-1", respectively. A design with totally possible arrangements of all the input factors is named a full factorial design in two levels. Based on fraction factorial design (FFD), 2^N (N: number of factor) simulation must be applied. Fractional factorial designs as espoused by traditional factional designs offer significant reductions in the number of experiments required. The reduced experimental costs, however, crime at the price of possible aliasing or mixing of the primary variable effects and the interaction effects. A full factorial design needs a huge number of runs and is not effective. In full factorial experiment design, a matrix containing all possible combinations of them is constructed, then the simulator is run using each combination. The values are selected to represent the entire range of variability of each parameter, in other words, the two extreme values of each uncertain variable are chosen [16, 17]. But, in Minitab software there is a way to reduce number of runs as resolution. Resolution defines the degree to which expected main effects are aliased (or confounded) with estimated 2-level interactions, 3-level interactions, etc. [16].

For investigation the effect of a factor during a process using experimental design, the effect of a factor is defined to be the modification in response produced by modify in the level of the factor. This is named a Main Effect because it mentions to the primary factor of notice in the experiment. The main effect of each parameter is defined as an equation in bellow [17]:

$$\text{Main effect} = (\text{Response value when variable has maximum value}) - (\text{Response value when variable has minimum value}) \quad (1)$$

Statistical significance of main and interaction effects can be evaluated by hypothesis testing. It is a standard method of statistical inference that considers two opposite hypotheses. The null hypothesis assumes that the effect of a parameter is negligible and the reported value is due to the chance or any other reason except the role of parameter itself. The alternative hypothesis assumes that the nonzero effects demonstrate the real effects of parameter. It is common to determine the credibility of null hypothesis with P-values. P-value describes how much it is probable that the null hypothesis be true [18]. More than, ANOVA is the best's statistical tool used in modeling the relationship between the response and the factors. A regression model for response parameter is generated based on ANOVA results. Regression models are particularly useful when one or more of the factors in the experiment are quantitative. A general linear model or a multiple regression model is [19]:

$$Y = \beta_0 + \beta_0 X_1 + \cdots + \beta_P X_P \quad (2)$$

Where Y is the response also called output or dependent variable, X_i is the predictor also called independent variables and β input or is the constant.

The numerical simulation software is considered to simulation all of the possible runs that have been produced from fractional factorial design. The response parameter (such as recovery factor in this study) is obtained from simulation run. Then the response parameter is included in experimental design to ANOVA analysis.

In the case of uses the combination of experimental design and numerical simulation, Bengar et al., 2017, studied the effective parameters on polymer flooding [15]. Also, Mohsenatabar Firozjaii and Moradi. S., 2018, studied the influence of effective parameters on polymer flooding compared to alkaline-surfactant-polymer (ASP) flooding [20].

2.1. Reservoir Mode

The compositional reservoir simulator, GEM, from the computer modeling group (CMG) were used for simulation of the Cartesian model. The quick pattern of 1/6 inverted 7 spot was considered for production and injection well pattern. As shown in figure 2, The Cartesian model have been girded in 43*22*2 i, j, and k direction, respectively. The other reservoir and well properties are summarized in table 1.

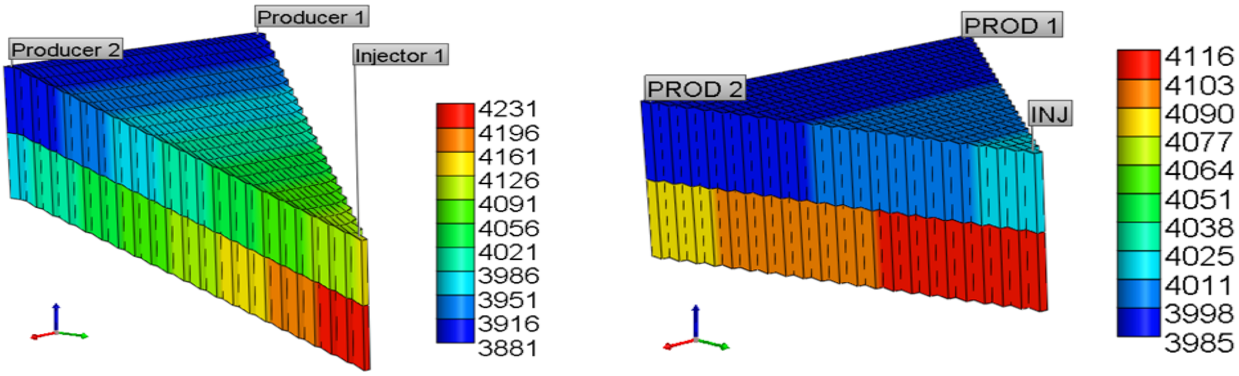

Fig 2. Reservoir model with reservoir dip angle 5°(Right) and 45°(left). The color legend shows the grid top.

As shown in figure 3, 4 cycles of gas and 5 cycles of water were considered to WAG four 9 years (2012-2021). The mixture of CO_2 and N_2 was considered for gas. The production and injection rate are summarized in table 1.

Table 1. Reservoir and wells properties.

Area	Porosity	Rock Type	Well Pattern	References Pressure	References Depth	BHP Production Wells	STW Injection Well	BHG Injection Well
10 Area	15%	Water wet	7 Stop	4000 psi	4216 ft	2500 psi	400bbl/Day	1000ft3/Day

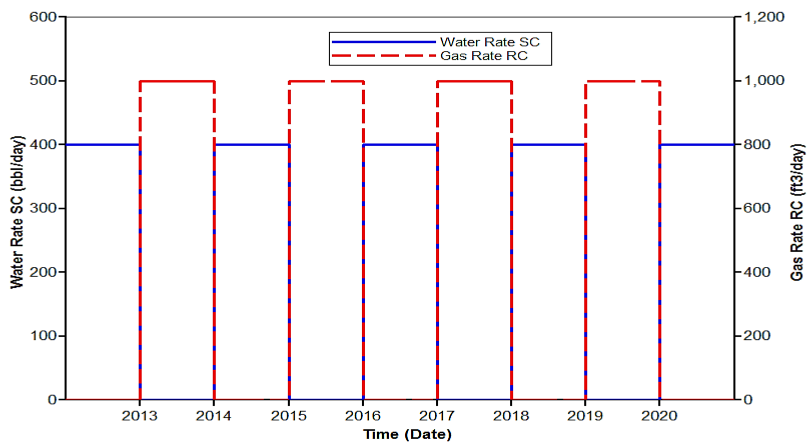

Fig 3. Water and Gas injection cycle.

2.1.1. Oil Component

The oil composition model was generated using Winprop (PVT module from CMG). The mole fraction of oil component is summarized in table 2. The molecular weight of oil was 243gr/gmol. Oil viscosity at 85F is considered 5cp.

2.2. Design of Experiment (DOE)

As shown in table 3, eight parameters that effect on oil recovery were selected with minimum and maximum value. Minitab software was considered for designing of the experiment's number. Fractional factorial design (FFD) $2^{(8-2)}$ was considered with resolution V (five) to 64 runs.

Table 2: oil component mole fraction [21].

Components	Oil (mol.%)
N_2	0.00
CO_2	0.00
C_2	0.08
C_3	1.10
iC_4	0.59
nC_4	2.38
iC_5	1.52
nC_5	1.92
C_6	7.81
C_7	4.20
C_8	2.52
C_9	4.88
C_{10}	5.52
C_{11}	4.34
C_{12}^+	63.14
Total	100.00
C_{12}^+: Mw = 325g/mol, SG = 0.9567	

Table 3: Variables and their limitation.

Variables	Min.	Max.
Temperature(T)	85°F	185°F
Reservoir thickness(H)	200ft	800ft
Horizontal Permeability(K_h)	100mD	1000mD
Oil Relative Permeability(Kro)	0.4	0.8
Gas Relative Permeability(Krg)	0.5	0.8
Connate Water saturation(Siw)	0.15	0.40
Reservoir Dip Angle(Dip)	5°	45°
Nitrogen Content(N_2)	0.3	0.7

3. Results and Discussion

As shown in table 4, the simulator performs 64 runs and the oil recovery factor was selected as response. By changing the level of each parameters (-1 or +1), the oil recovery factor has been modifying.

Table 4: Matrix of run.

Run	T	H	Kh	Kro	Krg	Siw	Dip	N_2	RF
1	85	200	1000	0.8	0.5	0.15	45	70	78.3
2	185	800	100	0.4	0.5	0.15	45	70	71.4
3	85	800	1000	0.8	0.8	0.15	5	70	68.7
4	85	800	100	0.4	0.8	0.15	5	70	67.8
5	85	200	1000	0.8	0.8	0.4	45	70	69.5
6	85	200	1000	0.4	0.5	0.4	5	30	68

7	85	800	100	0.8	0.5	0.15	45	30	73.4
8	185	800	100	0.4	0.8	0.15	45	30	71.7
9	185	800	100	0.8	0.5	0.15	5	70	71.3
10	85	200	100	0.4	0.8	0.15	45	30	76.7
11	185	800	1000	0.8	0.5	0.15	45	70	78.5
12	85	800	1000	0.8	0.5	0.15	5	30	72
13	185	200	100	0.4	0.8	0.4	5	30	77.2
14	85	200	1000	0.4	0.8	0.15	5	30	73.7
15	185	200	1000	0.8	0.5	0.4	5	70	72
16	85	800	1000	0.8	0.8	0.4	5	30	70.2
17	185	800	100	0.8	0.8	0.15	5	30	71.3
18	85	800	1000	0.8	0.5	0.4	5	70	70
19	185	800	1000	0.8	0.8	0.4	45	70	72.3
20	185	800	100	0.8	0.5	0.4	5	30	73
21	185	200	100	0.8	0.5	0.4	45	70	74.4
22	85	800	100	0.4	0.5	0.4	5	70	71.5
23	85	800	1000	0.4	0.5	0.4	45	70	72.4
24	185	800	1000	0.8	0.8	0.15	45	30	77.8
25	185	200	100	0.4	0.8	0.15	5	70	83.3
26	185	200	1000	0.8	0.8	0.15	5	70	76.6
27	185	200	1000	0.4	0.8	0.4	45	30	70.2
28	185	200	1000	0.4	0.5	0.4	45	70	70.7
29	185	800	1000	0.4	0.5	0.15	5	70	68.3
30	185	800	1000	0.8	0.5	0.4	45	30	72
31	85	200	100	0.8	0.8	0.4	5	70	80.9
32	185	200	100	0.8	0.8	0.15	45	70	77.2
33	85	800	100	0.8	0.5	0.4	45	70	69.1
34	85	800	100	0.4	0.8	0.4	5	30	71.2
35	185	200	100	0.4	0.5	0.15	5	30	86.1
36	85	200	100	0.8	0.5	0.15	5	70	86.5
37	85	200	100	0.8	0.5	0.4	5	30	85
38	85	200	1000	0.4	0.8	0.4	5	70	70.2
39	185	200	1000	0.8	0.5	0.15	5	30	76
40	185	200	100	0.8	0.5	0.15	45	30	77.5
41	85	200	100	0.4	0.5	0.15	45	70	77.5
42	85	800	100	0.8	0.8	0.15	45	70	72.1
43	185	800	100	0.8	0.8	0.4	5	70	73
44	85	200	100	0.8	0.8	0.15	5	30	87.5
45	185	800	1000	0.4	0.8	0.15	5	30	69
46	185	800	1000	0.4	0.8	0.4	5	70	68.7
47	185	200	100	0.4	0.5	0.4	5	70	79.5

48	185	800	1000	0.4	0.5	0.4	5	30	68.7
49	185	200	100	0.8	0.8	0.4	45	30	72.9
50	185	200	1000	0.8	0.8	0.4	5	30	70.6
51	85	800	1000	0.4	0.5	0.15	45	30	74.2
52	85	200	100	0.4	0.8	0.4	45	70	72.5
53	185	800	100	0.4	0.5	0.4	45	30	68.4
54	185	200	1000	0.4	0.8	0.15	45	70	76.6
55	85	800	1000	0.4	0.8	0.4	45	30	71.4
56	85	200	1000	0.4	0.5	0.15	5	70	75.3
57	85	200	1000	0.8	0.5	0.4	45	30	69.5
58	85	200	1000	0.8	0.8	0.15	45	30	77.5
59	85	200	100	0.4	0.5	0.4	45	30	71.6
60	185	800	100	0.4	0.8	0.4	45	70	68
61	85	800	100	0.8	0.8	0.4	45	30	69.5
62	85	800	1000	0.4	0.8	0.15	45	70	74.5
63	85	800	100	0.4	0.5	0.15	5	30	77.5
64	185	200	1000	0.4	0.5	0.15	45	30	76.3

3.1 One Factor Effect

For investigating of the parameters effect on oil recovery factor, main effect of each parameter was calculated using equation 1. As shown in table 5, each parameters have different effect and P-value. The P-value for temperature and nitrogen content is close to 1 and more than 0. When the P-value for a parameter has high value, it shows that parameter cannot be a good parameter for investigating the effect on response. But other parameters have P-value close to zero. Additionally, when the selected variable has maximum value, produce higher RF, it shows this parameter have positive effect but when the selected variable has minimum value, produce higher RF, it shows this parameter has negative effect.

Table 5: Statistical analysis of variables.

Variable	Effect	P-value
Temperature(T)	-0.1625	0.667
Reservoir thickness(H)	-4.6375	0
Horizontal Permeability(Kh)	-2.7125	0
Oil Relative Permeability(Kro)	1.4375	0.001
Gas Relative Permeability(Krg)	-0.8	0.042
Connate Water saturation(Siw)	-3.6875	0
Reservoir Dip Angle(Dip)	-1.09375	0.007
Nitrogen Content(N_2)	-0.28125	0.458

As shown in figure 7, Tornado plot was generated based on table 5. The Tornado plot is a useful graphically plot for sensitivity analysis comparing the relative importance of variables. Further, Tornado plot is a classic tool of sensitivity analysis to provide decision makers a quick overview of the risks involved and show a financial analysis for a project. As shown in Tornado plot, the oil relative permeability has a positive effect and other parameters have a negative effect. In fact, the oil recovery from WAG is more when oil relative permeability in maximum level (+1) compared to when it has minimum level (-1). In other words, WAG process have better performance when the oil relative permeability has large value. More than, WAG process have better performance when other parameters are in minimum level (-1) or have low value. Among these parameters, reservoir thickness has larger negative effect on oil recovery. It means WAG is affected by this parameter more than from other parameters.

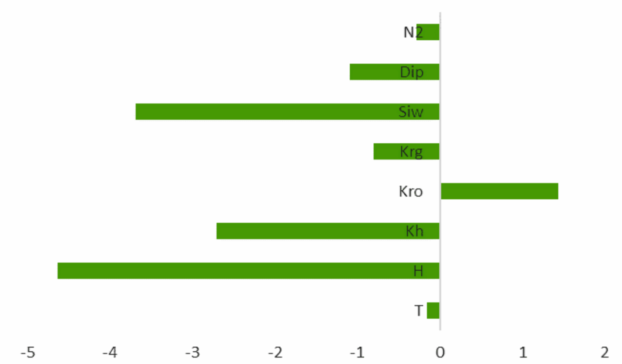

Fig 4. Tornado Plot.

3.2 Two Factor (Interaction Effect)

As shown in table 6, the interaction of two parameters have different behavior. Figure 5 shows the Pareto plot. The Pareto plot form table 6 shows the effect of one variable and interaction of two variables. The Pareto plot is extremely useful for analyzing which variable is more sensitive to change to responds or objective function. It seems interaction of reservoir dip angle (G) and horizontal permeability (C), CG, has larger effect compared to other variables.

Table 6: Interaction effect and P-value of two parameters.

Factor	IE	P-Value
T*H	0.031	0.934
T*Kh	0.719	0.065
T*Kro	-0.669	0.085
T*Krg	0.319	0.401
T*Siw	0.106	0.778
T*Dip	0.550	0.153
T*N2	0.475	0.215
H*Kh	3.244	0.000
H*Kro	-0.219	0.563
H*Krg	-0.106	0.778
H*Siw	1.806	0.000
H*Dip	2.625	0.000
H*N_2	-0.575	0.136
Kh*Kro	0.019	0.960
Kh*Krg	0.506	0.187
Kh*Siw	-0.494	0.198
Kh*Dip	3.825	0.000
Kh*N_2	0.625	0.106
Kro*Krg	0.119	0.753
Kro*Siw	0.044	0.908
Kro*Dip	-0.350	0.357
Kro*N_2	-0.050	0.895
Krg*Siw	0.331	0.383
Krg*Dip	0.500	0.192
Krg*N2	-0.125	0.741
Siw*Dip	-1.112	0.006
Siw*N_2	0.612	0.113
Dip*N_2	0.556	0.148

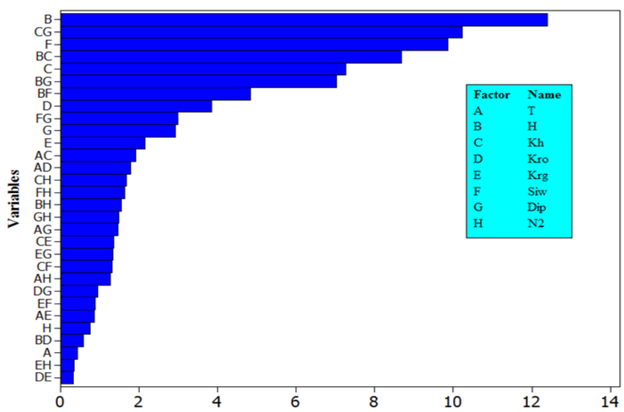

Fig 5. Pareto Plot.

3.3 Minimum and Maximum Oil Recovery

Based on table 4, minimum and maximum value of oil recovery factor was obtained from run 4 and 44. Figure 6 shows the oil recovery factor and oil production rate for run 4 and 44. In the maximum case, connate water saturation, horizontal permeability, thickness, temperature, and nitrogen content are at the lowest level but the relative permeability of oil has maximum value. But at the minimum case, the thickness of the reservoir and connate water saturation are in high level of value and other variables are at minimum level.

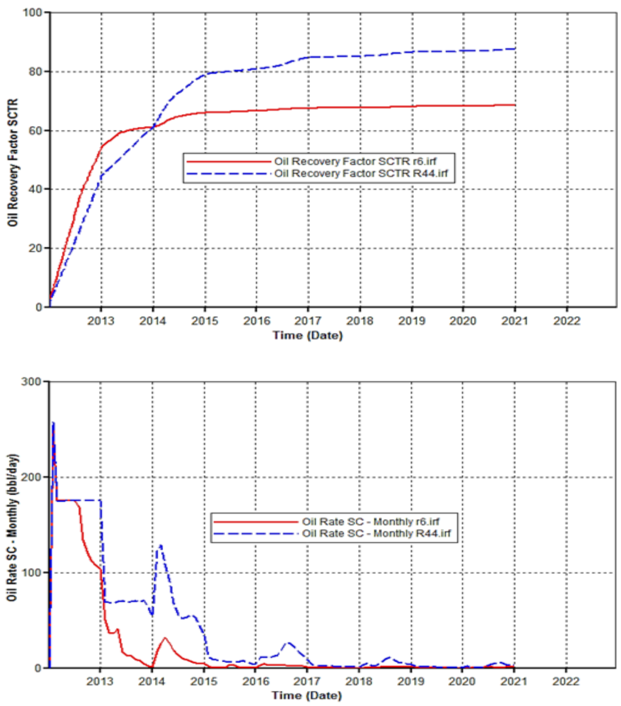

Fig 6. Oil recovery factor(left) and oil production rate monthly(right) when the simulation results show maximum (blue curve) and minimum (red curve) value of recovery factor.

As shown in figure 7, the relative permeability curve of water has same path in R-4 and -44, but the oil relative permeability curve has different path. It shows when oil recovery factor is maximum, oil relative permeability curve is put above the minimum oil recovery case and that is show the sweeping of oil in R-44 is better than R-4 (figure 8).

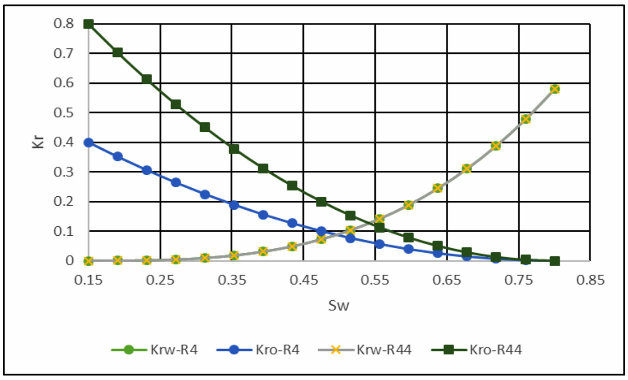

Fig 7. Relative permeability curve in run 4 and 44.

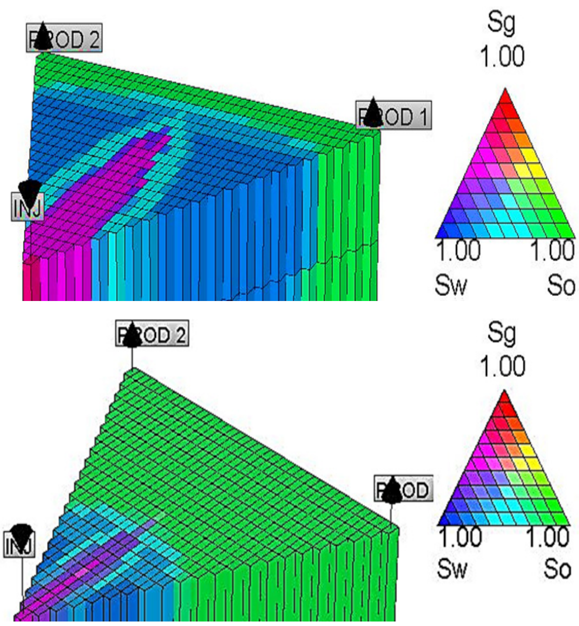

Fig 8. WAG flooding flow model. The figure shows the WAG process in R-44 (up) andR-4 (down) at the same time.

3.4 ANOVA and Regression Model

The oil recovery was calculated for all of 64 runs using stochastically analysis again. Then, the fractional factorial design results were analyzed using Minitab. As shown in figure 9, the ANOVA analysis as a strong correlation between simulation results and statistical results due to high correlation coefficient (R^2=0.95). Finally, a regression model using the results of ANOVA (as shown in table 7) was obtained. The regression model shows, the oil recovery factor for a reservoir from WAG process can be estimated when the reservoir properties are being known. This regression model can be helpful to determine the best candidate reservoir for applying WAG.

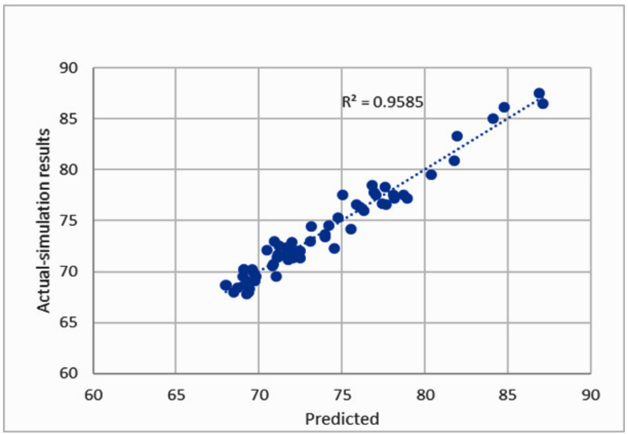

Fig 9. Regression model.

Regression model:

RF=73.84-0.08*T-2.31*H-1.35*Kh+0.71*Kro-0.4*Krg-1.84*Siw-0.54*Dip -0.14*N_2+0.0156*T*H+0.36*T*Kh-0.33*T*Kro+0.16*T*Krg+0.05*T*Siw+0.27*T*Dip+0.23*T*N_2+1.62*H*Kh-0.11*H*Kro-0.05*H*Krg+0.9*H*Siw+1.31*H*Dip-0.28*H*N_2+0.01*Kh*Kro+0.25*Kh*Krg-0.24*Kh*Siw+1.91*Kh*Dip+0.31*Kh*N_2+0.06*Kro*Krg+0.02*Kro*Siw-0.17*Kro*Dip-0.02*Kro*N_2+0.16*Krg*Siw+0.25*Krg*Dip-0.06*Krg*N_2-0.55*Siw*Dip+0.3*Siw*N_2+0.27*Dip*N_2.

Table 7: ANOVA table (DF: degree of freedom, MS: mean square, F: F-value, P: P-value).

Source	DF	MS	F	P	Coefficient
Variable	-	-	-	-	73.84688
T	1	0.423	0.19	0.667	-0.08125
H	1	344.103	153.96	0.000	-2.31875
Kh	1	117.723	52.67	0.000	-1.35625
Kro	1	33.062	14.79	0.001	0.71875
Krg	1	10.240	4.58	0.042	-0.4
Siw	1	217.563	97.34	0.000	-1.84375
Dip	1	19.141	8.56	0.007	-0.54688
N2	1	1.266	0.57	0.458	-0.14063
T*H	1	0.016	0.01	0.934	0.015625
T*Kh	1	8.266	3.70	0.065	0.359375
T*Kro	1	7.156	3.20	0.085	-0.33438
T*Krg	1	1.626	0.73	0.401	0.159375
T*Siw	1	0.181	0.08	0.778	0.053125
T*Dip	1	4.840	2.17	0.153	0.275
T*N2	1	3.610	1.62	0.215	0.2375
H*Kh	1	168.351	75.32	0.000	1.621875
H*Kro	1	0.766	0.34	0.563	-0.10938
H*Krg	1	0.181	0.08	0.778	-0.05312
H*Siw	1	52.201	23.36	0.000	0.903125
H*Dip	1	110.250	49.33	0.000	1.3125
H*N2	1	5.290	2.37	0.136	-0.2875
Kh*Kro	1	0.006	0.00	0.960	0.009375
Kh*Krg	1	4.101	1.83	0.187	0.253125
Kh*Siw	1	3.901	1.75	0.198	-0.24688
Kh*Dip	1	234.090	104.74	0.000	1.9125
Kh*N2	1	6.250	2.80	0.106	0.3125
Kro*Krg	1	0.226	0.10	0.753	0.059375
Kro*Siw	1	0.031	0.01	0.908	0.021875
Kro*Dip	1	1.960	0.88	0.357	-0.175
Kro*N2	1	0.040	0.02	0.895	-0.025
Krg*Siw	1	1.756	0.79	0.383	0.165625
Krg*Dip	1	4.000	1.79	0.192	0.25
Krg*N2	1	0.250	0.11	0.741	-0.0625
Siw*Dip	1	19.802	8.86	0.006	-0.55625
Siw*N2	1	6.002	2.69	0.113	0.30625
Dip*N2	1	4.951	2.22	0.148	0.278125

4.Conclusion

In this study compositional reservoir simulator GEM from CMG was used to generate the reservoir model. PVT model was generated by Winprop from CMG. Fractional factorial design (FFD) was considered to design the number of simulation runs using Minitab software. In this study, $2^{(8-2)}$ simulation was considered. The results show eight parameters were considered, have an effect on oil recovery factor. Based on Tornado plot, reservoir thickness (H) has the most effect on oil recovery factor when it has the minimum value. After that, connate water saturation has great effect on oil recovery factor when it has minimum level. Also, the result show reservoir dip angle, horizontal permeability, temperature, nitrogen content, and gas relative permeability have negative effect on oil recovery. But, oil relative permeability has maxim negative effect. More than, the interaction of two parameter reservoir dip angle and horizontal permeability has great effect on oil recovery after reservoir thickness. Finally, it seems the WAG process is a good choice for enhanced oil recovery (EOR) in case of the reservoir with low thickness and has high oil relative permeability. More than, a reservoir with low permeability and low dip angle is a good candidate to WAG.

Also, it is recommended to include heterogeneity of reservoir such as fracture factor, wettability, and rock types to future study.

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Nomenclature EOR: Enhanced oil recovery, CMG: Computer modelling group, GEM: Generalized Equation of State Model, WAG: Water alternating gas, IFT: Interfacial tension, BHP: Bottom hole pressure, STW: Surface water rate, BHG: Bottom hole gas rate, FFD: Fractional factorial design, DOE: Design of experiment, RF: recovery factor, ANOVA: Analysis of variance.

References

1. V. Alvarado and E. Manrique, “Enhanced oil recovery: an update review,” Energies, vol. 3, pp. 1529-1575, 2010.
2. S. Thomas, “Enhanced oil recovery-an overview,” Oil & Gas Science and Technology Revue de l’IFP, vol. 63, pp. 9-19, 2008.
3. A. Al Adasani and B. Bai, “Analysis of EOR projects and updated screening criteria, ”Journal of Petroleum Science and Engineering, vol. 79, pp. 10-24, 2011.
4. L. R. Brown, “Microbial enhanced oil recovery (MEOR),” Current opinion in Microbiology, vol. 13, pp. 316-320, 2010.
5. L. Koottungal, “Special Report 2010 worldwide EOR survey,” Oil & Gas Journal, vol. 108, pp. 41-53, 2010.
6. G. Nadeson, N. A. B. Anua, A. Singhal, and R. B. Ibrahim, “Water-Alternating-Gas (WAG) Pilot Implementation, A First EOR Development Project in Dulang Field, Offshore Peninsular Malaysia,” 2004.
7. J. R. Christensen, E. H. Stenby, and A. Skauge, “Review of WAG Field Experience,” 1998.
8. S. M. Ghaderi, C. R. Clarkson, and Y. Chen, “Optimization of WAG Process for Coupled CO2 EOR-Storage in Tight Oil Formations: An Experimental Design Approach,” 2012.
9. M. M. Kulkarni, “Immiscible and miscible gas-oil displacements in porous media,” 2003.
10. L. Surguchev, E. Manrique, and V. Alvarado, “Improved Oil Recovery: Status and Opportunities,” 2005.
11. S. Chen, H. Li, D. Yang, and P. Tontiwachwuthikul, “Optimal Parametric Design for Water-Alternating-Gas (WAG) Process in a CO_2-Miscible Flooding Reservoir, ”Journal of Canadian Petroleum Technology,

vol. 49, pp. 75-82, 2010.

12. H. Panjalizadeh, A. Alizadeh, M. Ghazanfari, and N. Alizadeh, "Optimization of the WAG injection process," Petroleum Science and Technology, vol. 33, pp. 294-301, 2015.

13. M. Dong, J. Foraie, S. Huang, and I. Chatzis, "Analysis of immiscible water-alternatinggas (WAG) injection using micromodel," in Canadian International Petroleum Conference, 2002.

14. L. Surguchev, R. Korbol, S. Haugen, and O. Krakstad, "Screening of WAG injection strategies for heterogeneous reservoirs," in European petroleum conference, 1992.

15. A. Bengar, S. Moradi, M. Ganjeh-Ghazvini, and A. Shokrollahi, "Optimized polymer flooding projects via combination of experimental design and reservoir simulation," Petroleum, 2017.

16. C. Croarkin, P. Tobias, J. Filliben, B. Hembree, and W. Guthrie, "NIST/SEMATECH ehandbook of statistical methods," NIST/SEMATECH, July. Available online: http://www.itl. nist. gov/div898/handbook, 2006.

17. D. C. Montgomery, "Design and analysis of experiments. John Wiley & Sons, New York," Design and analysis of experiments. 7th ed. John Wiley & Sons, New York., 2009.

18. R. J. Larsen and M. L. Marx, Introduction to Mathematical Statistics and Its Applications: Pearson New International Edition: Pearson Higher Ed, 2013.

19. W. J. M. Al-Mudhafer, "A comparative thermal IOR simulation study with experimental design for optimal future performance of a heterogeneous light oil reservoir," in SPE Western Regional & AAPG Pacific Section Meeting 2013 Joint Technical Conference, 2013.

20. Ali Mohsenatabar Firozjaii and S. Moradi, "Sensitivity Analysis and Optimization of the Effective parameters on ASP Flooding Compared to Polymer Flooding Using CMGSTARS. ," Journal of Petroleum & Environmental Biotechnology, vol. 9, 2018.

21. M. Abdi, "Experimental investigation effects of asphaltene deposition on relative permeability during water alternating gas (WAG) injection process," Master, Abadan Faculty of Petroleum Engineering, Department of Petroleum Engineering, Petroleum University of Technology, 2013.

تحلیل حساسیت برروی پارامترهای موثر بر تزریق متناوب آب و گاز به منظور ازدیاد برداشت

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چکیـــــده

روش های ازدیاد برداشت به منظور افزایش تولید پس از تولید طبیعی از مخزن به کار گرفته می شود. هریک از روش های ازدیاد برداشت با توجه به خصوصیات سنگ و سیال مخزن دارای محدودیت هایی هستند. در روش تزریق متناوب آب و گاز، پارامترهای مختلفی شامل ضخامت مخزن، تراوایی افقی، و اشباع اولیه آب برروی میزان ضریب بازیافت نفت تاثیر می گذارند. در این مطالعه، پارامترهای مهمی که برروی تزریق متناوب آب و گاز تاثیر دارند، مورد بحث قرار گرفته اند. نرم افزار شبیه سازی مخزن CMG-GEM برای شبیه سازی و نرم افزار مینی تب برای طراحی و تحلیل آماری پارامتر ها مورد استفاده قرار گرفتند. نتایج نشان می دهد که ضخامت مخزن و اشباع اولیه آب تاثیر قابل ملاحظه ایی بر روی ریکاوری دارند به طوری که این مقادیر در کمترین حد باشد تاثیر مثبت است، و ریکاوری بیشترین مقدار را دارد. از طرفی دیگر، اثر برهمکنش دو پارامتری، شیب مخزن با تراوایی افقی تاثیر قابل ملاحظه ایی بر ضریب بازیافت دارند. براساس نتایج این مطالعه می توان یک مخزن کاندید برای تزریق WAG را انتخاب کرد.

واژگان کلیدی: EOR،تزریق متناوب آب و گاز، GEM،CMG،WAG، بهینه سازی