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Investigating the Effects of Heterogeneity, Injection Rate, and Water Influx on GAGD EOR in Naturally Fractured Reservoirs

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Abstract

The gas-assisted gravity drainage (GAGD) process is designed and practiced based on gravity drainage idea and uses the advantage of density difference between injected CO_2 and reservoir oil. In this work, one of Iran western oilfields was selected as a case study and a sector model was simulated based on its rock and fluid properties. The pressure of CO_2 gas injection was close to the MMP of the oil, which was measured 1740 psia. Both homogeneous and heterogeneous types of fractures were simulated by creating maps of permeability and porosity. The results showed that homogeneous fractures had the highest value of efficiency, namely 40%; however, in heterogeneous fractures, the efficiency depended on the value of fracture density and the maximum efficiency was around 37%. Also, the effect of injection rate on two different intensities of fracture was studied and the results demonstrated that the model having higher fracture intensity had less limitation in increasing the CO_2 injection rate; furthermore, its BHP did not increase intensively at higher injection rates either. In addition, three different types of water influxes were inspected on GAGD performance to simulate active, partial, and weak aquifer. The results showed that strong aquifer had a reverse effect on the influence of GAGD and almost completely disabled the gravity drainage mechanism. Finally, we inventively used a method to weaken the aquifer strength, and thus the gravity drainage revived and efficiency started to increase as if there was no aquifer.

Keywords: Gravity Drainage, Naturally Fractured Reservoirs, GADG, CO_2 Gas Injection, Heterogeneity, Fracture Intensity

1. Introduction

The stranded oil resources left behind after primary and secondary recovery processes have been estimated to exceed nearly two trillion barrels worldwide. The literature clearly shows that gas-injection-based EOR methods are ideal processes used in every type of reservoir and feasible alternatives that can tap into and effectively recover this enormous resource base. Worldwide EOR surveys by the *Oil and Gas Journal* (April 21, 2008) during the last two decades clearly show the increased popularity and production share of gas injection processes in the world. According to studies, the share of production from gas injection EOR has almost been tripled from 18% in 1984 to 58% in 2006 (Kulkarni et al., 2006). Overlay continuous gas injection (CGI) process was the basic mode of horizontal flood gas injection (especially CO_2) in many oil reservoirs; nevertheless, it encountered two very vital issues, namely gas gravity overriding and very poor sweep efficiency. In order to improve the CGI flaws, in 1958, Caudle and Dyes demonstrated the water alternating gas

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(WAG) process which simultaneously used water (to lower the density difference) and CO_2 (to increase the microscopic efficiency and thereby the overall efficiency) in recovery from oil reservoirs (Chakravarthy et al., 2006; Novosel, 2005). Thus, it was expected that a combination of water and gas in alternate slugs could yield optimum benefits; however, due to gas tendency to rise and water preference to descend, it was observed that low E_V still was one of the major problems. Despite this drawback of the WAG process, nearly 80% of the commercial gas injection EOR processes employ this process today (Kulkarni et al., 2006). As an alternative choice to the WAG process, Green and Willhite recommended that this density difference could be used as an advantage in dipping reservoirs to gain higher sweep efficiency and introduced gravity drainage mechanism (Green and Willhite, 1998). The gravity mechanism is one of the most efficient mechanisms of producing from oil reservoirs. Field reviews (Kulkarni, 2004) on nine commercial gravity stable gas floods in pinnacle reefs and/or dipping reservoirs demonstrated that all the gravity stable floods were highly successful in recovering residual oil from these reservoirs. Contrary to the WAG process, gravity stable gas floods in dipping reservoir and pinnacle reefs have proved to be one of the most efficient methods in oil recovery. Therefore, the gravity-stable gas injection process could very well be an alternative to the presently applied WAG process.

2. Gas-assisted gravity drainage

Gas-assisted gravity drainage EOR process based on gravity dominant flood uses the advantage of density difference between gas (especially N_2 and CO_2) and reservoir oil. It was first designed and practiced by Rao et al. in 2001 in L.S.U. to overcome the common problems of conventional gas injection methods. The strength point of GAGD is to diminish the water shielding problems and also reclaim the poor sweep efficiency of the WAG process (T. N. Mahmoud and D. N. Rao, 2008). The main intent of gravity drainage is to apply the in situ segregation of fluids by injecting gas into the crest of the pay zone, and then creating pressure maintenance forcing the oil downward the horizontal producing well, which leads to better volumetric sweep efficiency and higher ultimate oil recovery as well. GAGD consists of two vertical injection wells into the crest, which especially use CO_2, and a horizontal production well in the bottom of pay zone; it is noteworthy that the horizontal production well is one of the main factors improving sweep efficiency in this process. Figure 1 shows the schematic representation of gas-assisted gravity drainage. In this paper, our endeavor is to numerically simulate the GAGD process in naturally fractured reservoirs, which have rarely been studied in the field of GAGD EOR, and to investigate the effect of fracture parameters and water influx on its efficiency.

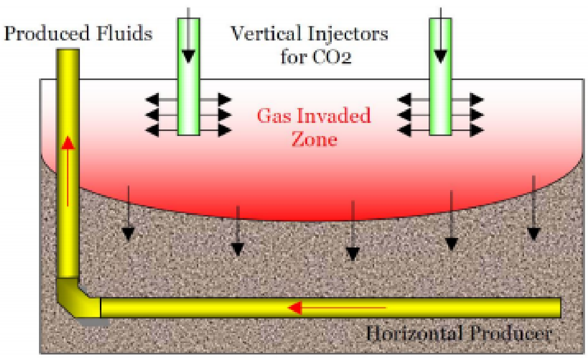


Figure 1
A schematic of gas-assisted gravity drainage (GAGD) process, (Rao, 2001)

3. Numerical simulation

The case study chosen in this work was one of the naturally fractured Iran oil fields and a comprehensive simulation was considered for a specific sector model of it. Since the case had randomly distributed fractures, a uniform random number generator (using MATLAB package) was used to generate the appropriate map of its distribution. An advanced 3-D dual porosity/dual permeability sector model using ECLIPSE 100 which was created based on the rock and fluid properties of our case study was employed in this study. The numerical equations were set to be solved by a fully implicit method. Table 1 and Table 2 show the rock and fluid properties used in the simulation process. It was observed that the field was reinforced by an active water influx which seemed to disable the performance of any gas injection EOR processes.

Table 1

Rock properties of the studied reservoir

Property	Value	Property	Value
API	41	WOC (ft)	2600
Oil density (lbm/ft^3)	41	Average permeability (md)	1
Gas density (lbm/ft^3)	0.049	Matrix porosity (%)	10
Oil FVF (Rbbl/stb)	1.34	Water compressibility (1/psi)	2.12×10^{-6}
Water FVF (Rbbl/stb)	1.01	Rock compressibility (1/psi)	4.29×10^{-6}
Oil viscosity (cp)	0.65	Reservoir temperature (°F)	118
Gas viscosity (cp)	0.019	Average reservoir pressure at datum depth (psi)	1550
Water viscosity (cp)	0.18	Initial pressure (psi)	2400
GOR (ft^3/scf)	800		

Additionally, field water cut values were reported to be considerably high because of its highly fractured reservoir rock; hence, the water flooding scenario could be such an absolute failure. At the beginning, the simulation study was supposed to evaluate the effect of heterogeneity on the performance of GAGD gas injection and then find the best scenario to enhance the light oil recovery from the reservoir. Although water flooding as a pressure maintenance process was expected to have low efficiency, water cut value showed a margin of discretion for the future plan. As a result, the assessment of the future production scenario of this oil field, which considerably contained a great amount of light and high graded oil, had to be done carefully.

Table 2

Fluid properties of the studied reservoir

Component	Molar %	Component	Molar %
H_2S	0.6262	NC_4	5.475
CO_2	0.8941	IC_5	1.6318
C_1	29.884	NC_5	1.2729
C_2	8.4317	C_{6+}	43.17
C_3	5.9195	M.W. of C_{6+}	199 g/g.mol
IC_4	2.1548	S.G. of C_{6+}	0.8181

4. Results and discussion

A 20×20×30 sector model with a similar length, width, and height equal to 50 ft was considered as our sector model to be simulated to anticipate the behavior of Iran oil field during the GAGD injection. The fracture view of the simulated sector model is shown in Figure 2.

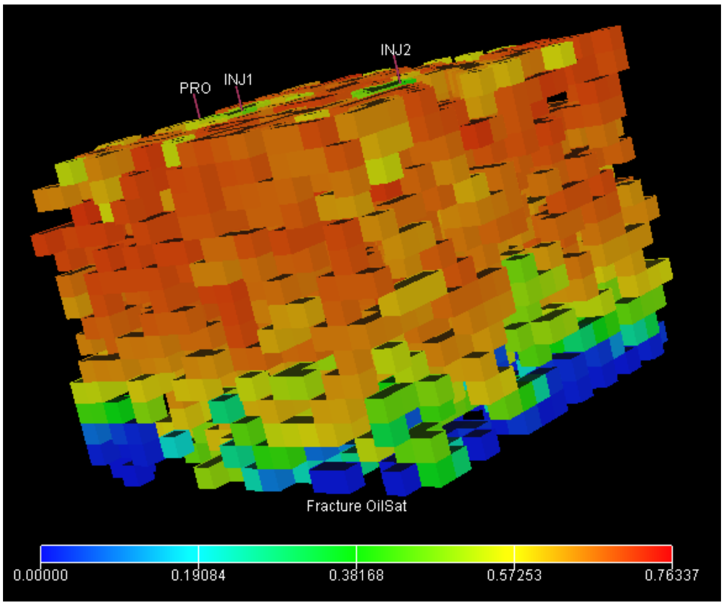


Figure 2
Fracture view of the simulated sector model

4.1. Miscibility range

Since the sector model was considered for near MMP gas injection, the MMP of CO_2 injection in the reservoir had to be first computed. The API gravity of the oil field was 41°, while the recent reservoir pressure reported value was 1550 psia. With the extra light oil and CO_2 injection, MMP was evaluated with slim tube and minimum miscibility pressure value was measured 1740 psia. Therefore, the injection pressure had to be kept below this value not to reach the miscibility condition. In fact, by using a specific keyword in E-100, MMP range and the injection rate were simultaneously controlled.

4.2. Effect of homogeneity and heterogeneity

Due to the fact that the distribution of oil within the pore spaces of the porous media plays an important role in the viability of any EOR process, the very only effective mechanism for gas injection EOR, especially CO_2, to be used in NFRs is gravity dominant flooding. Although the homogeneity in fractures may never exist in real cases, the difference between heterogeneous and homogenous cases had to be observed with maximum validation to minimize the off range speculations. The 20×20×30 grid model used equal values of 5 md for the permeability of matrix, 1000 md for the x and y permeability of fracture, and 100 md for z permeability of fracture as real values computed from cores. The matrix porosity and the fracture porosity values were set to 0.2 and 0.02 respectively. No further changes were considered in the homogenous mode and the model was simulated to observe the respective results. The heterogeneous case, which was most likely similar to the real reservoir, was presented with four different fracture intensity (FI) values.

The map of heterogeneity was built based on the determined fracture intensity values, and then the maps of fracture and matrix permeability (K_{eff}) were prepared to vary from 1000 to1500 md and from

2 to 5 md respectively. Table 3 represents the matrix and fracture specifications in details. By using DPNUM keyword in E-100 and considering the four different values of fracture intensity, various heterogeneous cases with a variety of fracture densities were defined and included in the simulator as well. The simulation was carried out and the results were extracted for an injection rate of 200 MSCF and a duration time of 500 days. As shown in Figure 3A, the maximum efficiency in the presence of heterogeneous fractures was variable from 30 to 37%. However, the CO_2 injection efficiency for the homogenous case was 40%.

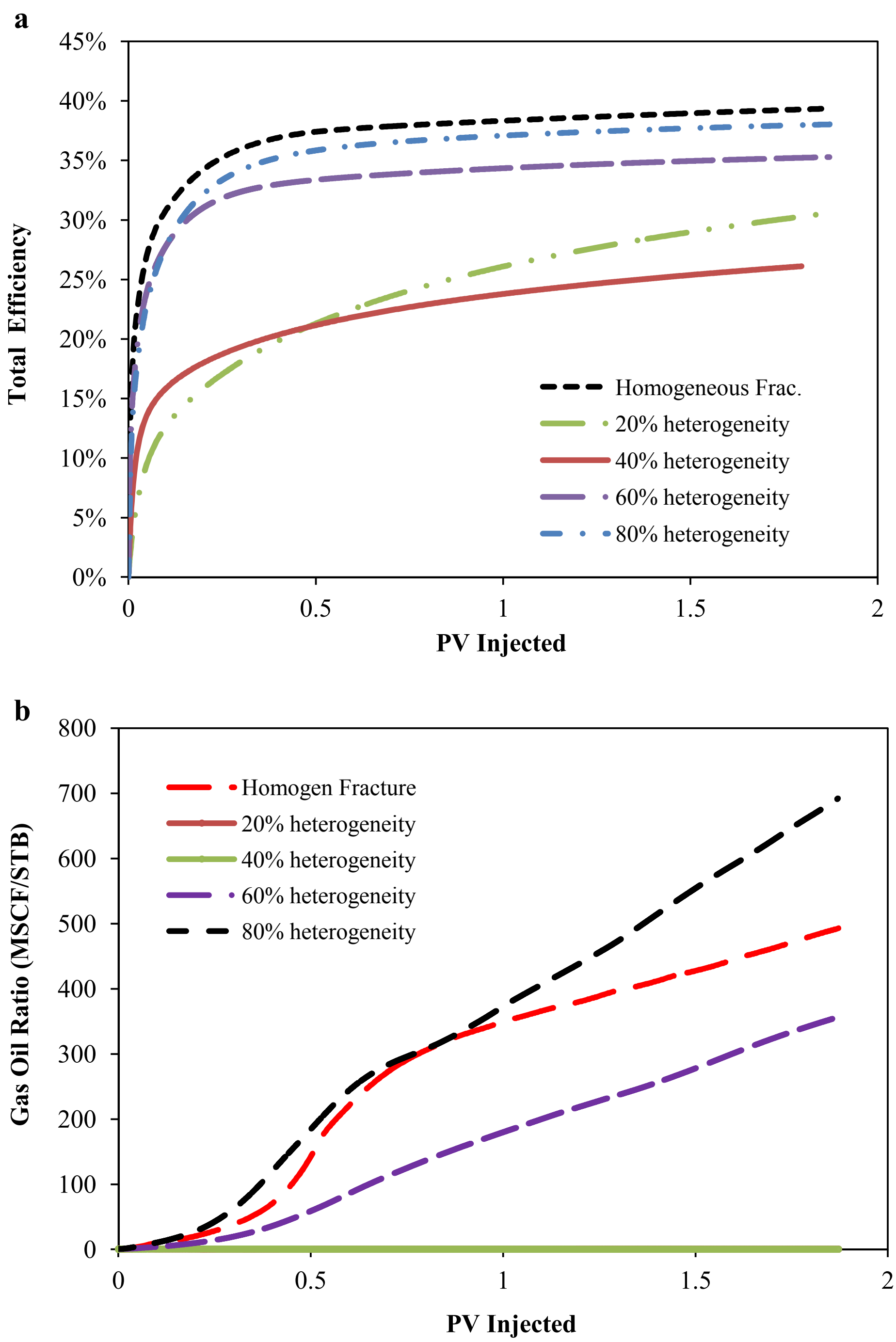


Figure 3
Effect of injection rate in heterogeneous fracture with a fracture intensity of 0.8: (A) FOE; (B) FGOR.

Table 3
Fracture properties of simulated model

Type of porous medium	Fractured	X grid block size (ft)	5
Number of cell in x-direction (N_x)	20	Y grid block size (ft)	5
Number of cell in y-direction (N_y)	20	Z grid block size (ft)	5
Number of cell in z-direction (N_z)	30	Matrix porosity (%)	5
Number of cell	12000	Fracture permeability (md)	1500
Dual porosity matrix-fracture coupling (1/ft^2)	0.75	Effective matrix block height for gravity drainage (ft)	10

Furthermore, Figure 3B shows the GOR results from both cases; it could be concluded from the results that, for non-homogeneous reservoirs, an increase in rock heterogeneity and fracture density increases efficiency and results in more oil production; nevertheless, the breakthrough time will be shorter and higher GOR have to be expected. It should be mentioned that there are some exceptions for FI=0.2 and FI=0.4 in the given graphs; therefore not only the overall efficiency, but also the GOR and GPR of these two values are not similar to the others. This is the cause of limited control on the BHP pressure of the injection wells in which the pressure was not allowed to reach the value beyond the MMP; thus the rates were reduced until the pressure dropped. For these two values at a rate of 200 MSCF, after a certain time of injection, wells were closed because of the listed reasons.

4.3. Effect of rate

The very first point that is considerably important is the rate sensitivity of fractures; this means before any barrel of production care must be taken to intend the critical production rate not to increase the drawdown carelessly, otherwise fractures rapidly deplete and the rest bulk of oil, which exists in the matrix, will be intact and somehow trapped in the reservoir without required force to be produced. If so, during the gas injection the high rate of production could mislead the front of gas to the fractures and thus leads the gas to be produced instead of helping the oil coming out of the pores. As mentioned before, the recent measured pressure of the respective reservoir was 1550 and the minimum miscibility pressure of CO_2 injection was measured 1740 psia. Therefore, the control of BHP had to be applied alongside the ability which various rates could be tested. Two cases of fractures with a fracture intensity of 0.8 and 0.2 were considered and four different rates for each fracture intensity were chosen to observe the effects of rate. Within the keyword WCONINJE, the main control of injection wells was set as “RATE” control and BHP limit value was set to 1700 psia.

Figures 4 and 5 both show the results of the effect of different rates on GAGD in two different cases of heterogeneous fractures. In the case of fracture with a fracture intensity of 0.2, as can be seen, rates of 10 and 50 MSCF were chosen for the beginning and efficiency increased with rate; however, at the higher rates, namely 100 and 200 MSCF, the efficiency did not increase at all and fell slowly, which indicated that the BHP control of injection wells set in the simulation did not allow the injection pressure to reach values higher than 1700 and thus rate started to decrease slowly. The gas to oil ratio shows how rates of 100 and 200 MSCF did not performed well and were decreased or stopped by the simulator control. For further results, the effect of various rates on fractures with a fracture intensity of 0.8, which has more fractures and connected pores, was inspected as well. Figure 4 demonstrates the overall efficiency, total production, and gas to oil ratio respectively. It is clearly understandable that, in comparison with fractures with a fracture intensity of 0.2, higher efficiency could be obtained. Firstly, the variety of flow paths provides more pores for gas to deplete oil from them. Secondly, higher transmissibility due to high permeable fractures helps the depleted oil move toward the production well easily. Furthermore, higher transmissibility helps the gas flow more easily; therefore, the accumulation of gas is decreased and the BHP of injection wells does not increase easily and hence the value of rate can be increased without any obstacle.

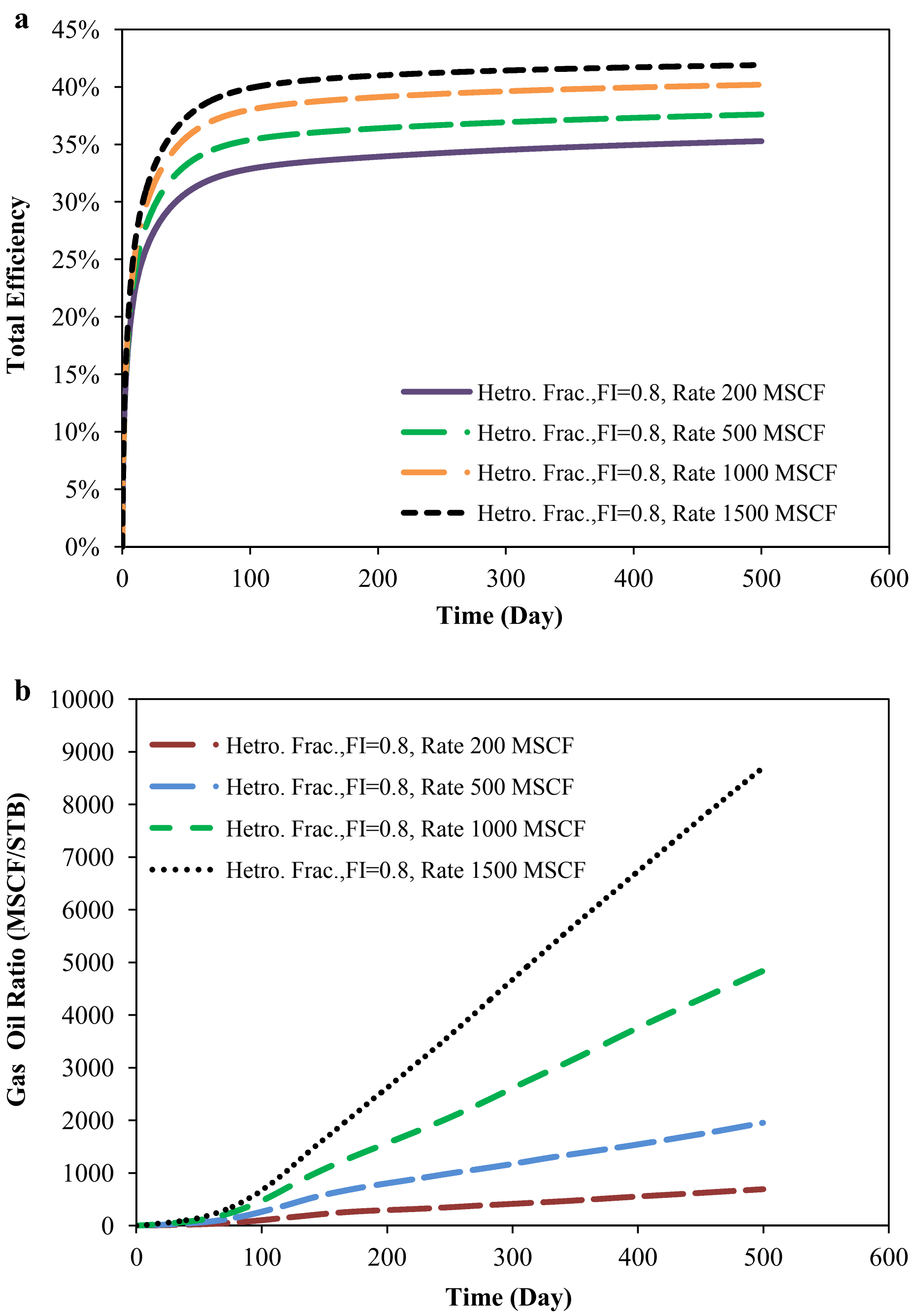
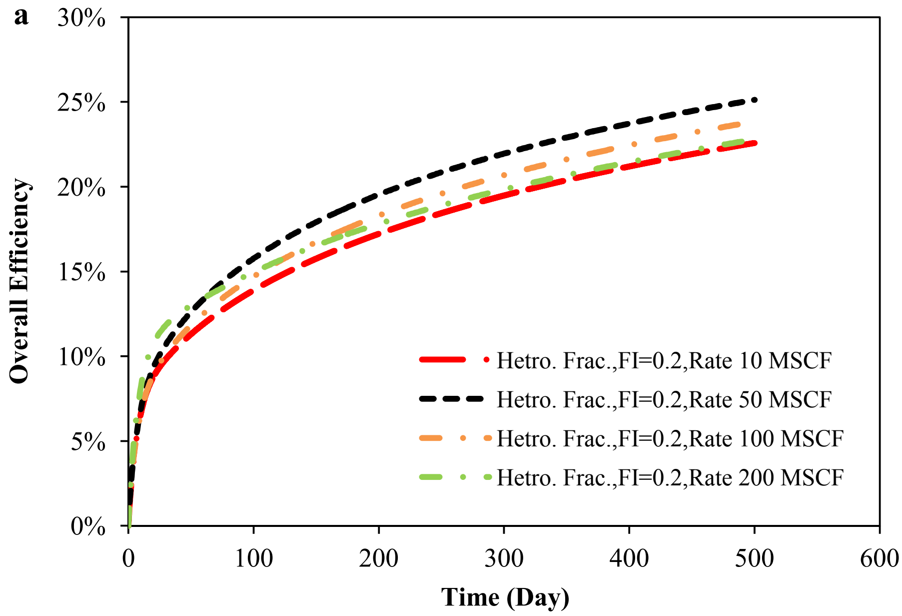


Figure 4
Effect of heterogeneity and homogeneity: (A) FOE; (B) FGOR.



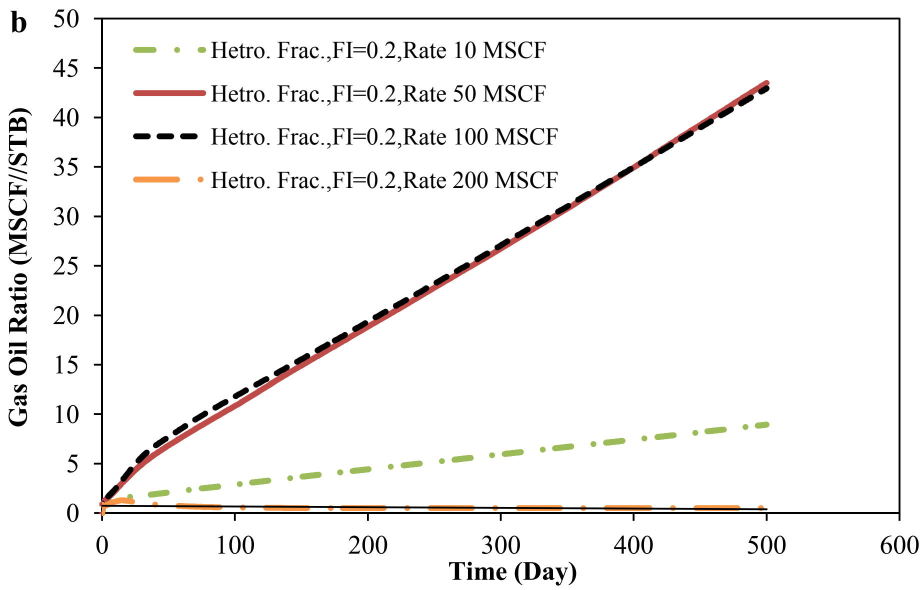


Figure 5
Effect of rate in a heterogeneous fracture with a fracture intensity of 0.2: (A) FOE; (B) FGOR.

4.4. Effect of water influx

In order to evaluate the aquifer effect on the performance of GAGD, an aquifer with Fetkovich model and a productivity index (PI) equal to 100 (STBD/psia) was considered to simulate the active water influx that surrounded the major part of the mentioned oil field. Moreover, two other cases of aquifer with a productivity index of 0.1 and 1 were simulated to fulfill the partial and weak aquifer as well. The results with and without aquifer were observed and were in agreement with our expectations. Due to aquifer strong pressure maintenance, the injected gas could not deplete the mass of oil out of the matrix and, as a result, was trapped at the crest point. This phenomenon continued until fractures sufficiently depleted bulk of oil and drawdown helped the gas to find a path toward the production well. Therefore, without any significant impact on the matrix, gas passed and no gravity drainage process existed. Figure 6A clearly shows the efficiency difference between the case with aquifer and the case without it. As can be seen, active aquifer further diminished the GAGD performance and disabled the gravity drainage process. In addition, partial and weak aquifers, which do not maintain the reservoir pressure very much, provided a better condition for the gravity drainage process to respond better. As a result, compensating the drawdown in GAGD EOR was not helpful at all and made the process act as a useless method wasting money and time. To fulfill the GAGD EOR in such conditions, we should have omitted this issue, or at least debilitated the aquifer strength, to let the reservoir pressure descend and then inject CO_2 to form the desirable gravity drainage process. Then, in the first mode, one vertical production well was considered in the aquifer zone to produce the water and therefore reduce the strength of pressure maintenance.

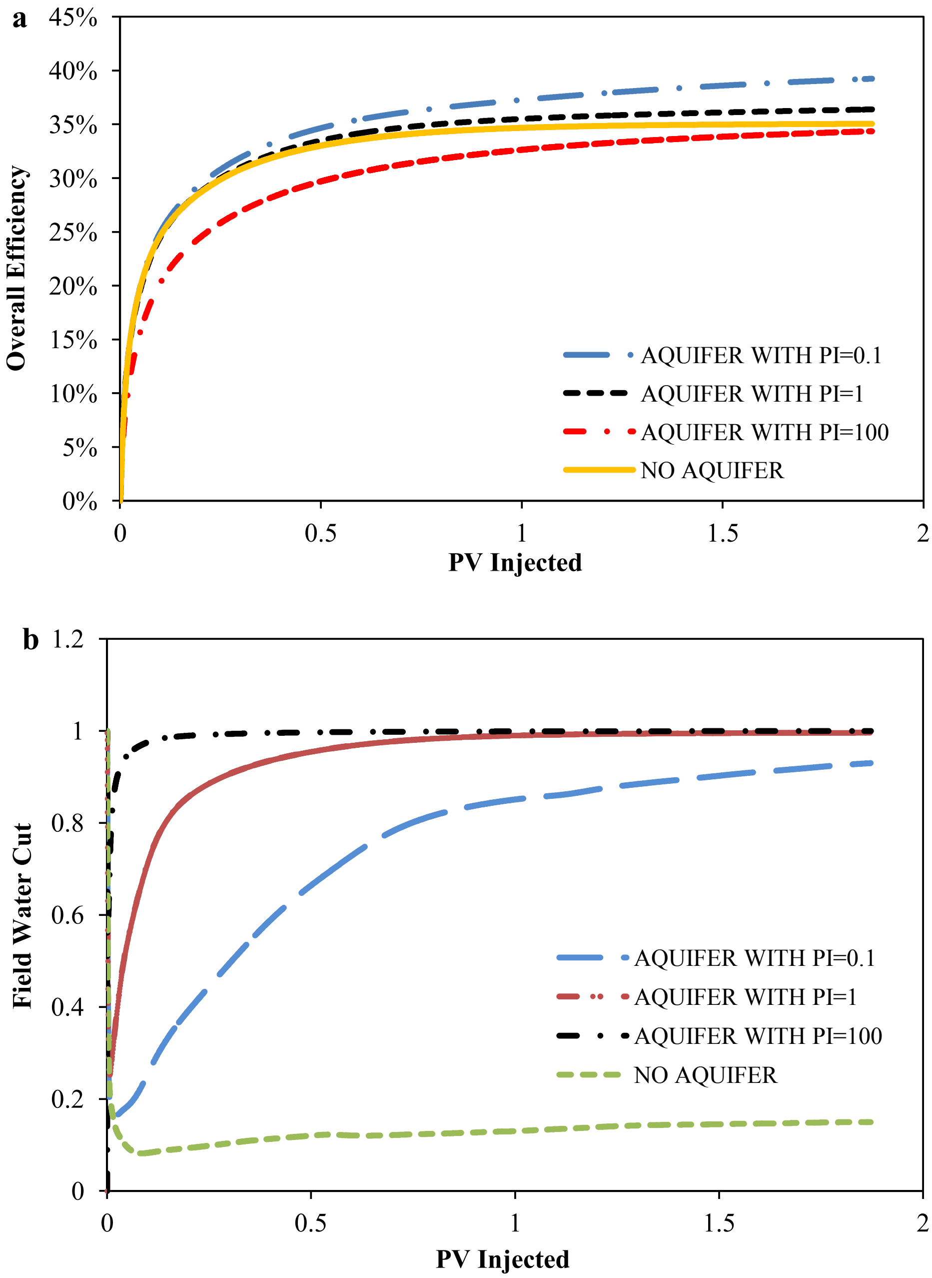


Figure 6
Effect of weakening the aquifer with a vertical producing well in water zone: (A) FOE; (B) FGOR.

Figure 7 shows the GAGD behavior after and before debilitating the aquifer strength. In the case in which aquifer was widespread enough to affect the reservoir severely, two vertical wells were intended to be bored in the water zone and depleted the water twice as much. As shown below, the highest efficiency was gained when two vertical wells were completed in aquifer zone with a productivity index of one.

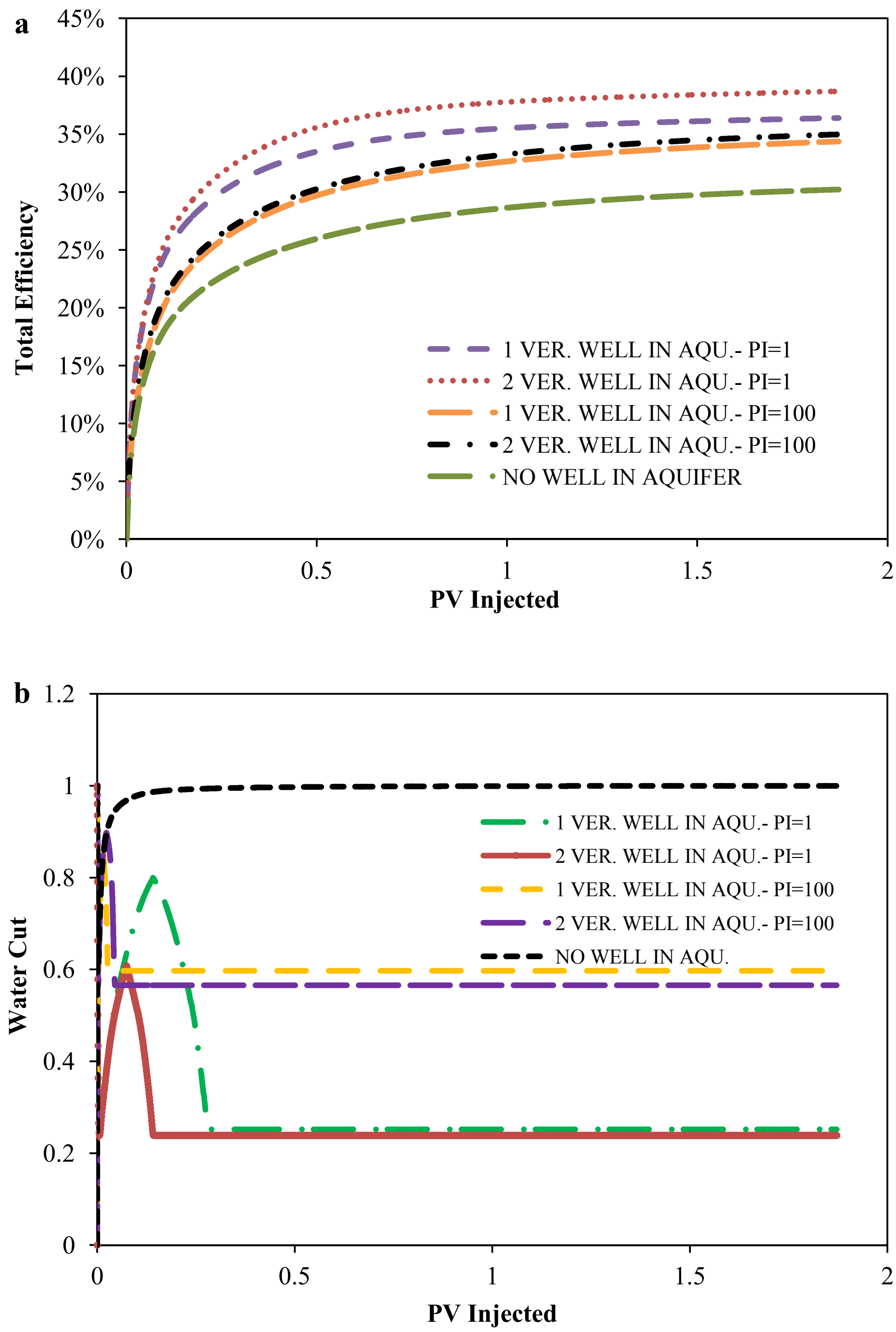


Figure 7
Effect of active, partially active, and weak aquifer in comparison with no aquifer: (A) FOE; (B) FOPT.

Although two vertical wells were considered for the aquifer with a productivity index of 100, the higher strength of the second aquifer affected the system severely and efficiency index was then lower, and thus GAGD performed weaker in the second case. The third case contained no well in aquifer and expectedly had the lowest efficiency specifically because of the active aquifer acting there. As a result, the more the water was produced from the aquifer, the higher the efficiency of gas injection improved.

6. Conclusions

The results from the simulation are represented based on the observations inferred from this study and several conclusions can be made:

1. Although homogeneous fractures have rarely been found in the field, they were a perfect choice for operating GAGD) and resulted in efficiency of 40%.
2. Heterogeneity strongly affected the efficiency of GAGD and therefore a very precise reservoir characterization had to be done to evaluate the degree of heterogeneity in order to set every aspect of GAGD CO_2 injection.
3. In case of fracture density, fractures with fracture intensity of 0.8 lead to the highest efficiency compared to the others, namely fracture intensities of 0.2, 0.4, and 0.6.
4. The results showed that in the case having a fracture intensity of 0.2 CO_2 injection rate could not accept a value higher than 100 MSCF due to increasing the BHP of injection wells. Nevertheless, in the case with fracture intensity of 0.8, the transmissibility of which was considerably higher, the injection rate value could be set to even 1500 MSCF without any limitation.
5. Fracture efficiency of the case with a fracture intensity of 0.2 was near 25%, whereas it was 40% for the case having a fracture intensity of 0.8.
6. To investigate the effect of rate care must be taken about the BHP of the injection wells and also the rate of production must carefully be set because the NFRs are very rate sensitive.
7. It was concluded from the simulation that water influx, on the basis of its strength, could affect the CO_2 GAGD performance; an aquifer with a productivity index of 100 STBD/psi diminished the efficiency of the process very much, while the others slightly weaken it.
8. The solution to eliminating the effect of aquifer was achieved by completing at least one vertical producing well in water zone and producing water as much as possible.

The number of producing wells from water zone depends directly on the strength of the aquifer. The results showed that the more the aquifer could be debilitated, the higher the efficiency of GAGD gas injection became.

Nomenclature

BHP	: Bottom hole pressure
CGI	: Continuous gas injection
cp	: Centipoise
E_D	: Microscopic efficiency
EOR	: Enhanced oil recovery
E_V	: Volumetric efficiency
FGOR	: Field gas oil ratio
FOE	: Field efficiency
FOPR	: Field oil production
FOPT	: Field total oil production
FPR	: Field pressure
FI	: Fracture intensity
FVF	: Formation volume factor
FWCT	: Field water cut
GAGD	: Gas-assisted gravity drainage

GOR	: Gas oil ratio
GPR	: Gas production
K_{eff}	: Effective permeability
lbm	: Pound mass
md	: Millidarcy
MMP	: Minimum miscibility pressure
MSCF	: Million standard cubic feet
M.W.	: Molecular weight
NFR	: Naturally fractured reservoir
NISOC	: National Iranian South Oil Company
PI	: Productivity index
psi	: Pounds per square inch
psia	: Pounds per square inch absolute
PV	: Pore volume
Rbbl	: Reservoir barrel
scf	: Standard cubic feet
S.G.	: Specific gravity
stb	: Stock tank barrel
STBD	: Stock tank barrel per day
WAG	: Water alternating gas
WOC	: Water oil contact

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