The Performance of Gas Assisted Gravity Drainage Process - Parametric Investigation

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Abstract:

Gas Assisted Gravity Drainage (GAGD) process is an immiscible gas injection Improved Oil Recovery (IOR) technique that is designed to take advantage of gravity force that allow vertical segregation between injected gas and reservoir crude oil. This segregation is due to the density difference between oil and gas. The GAGD process uses vertical injection wells at the top of the reservoir, and horizontal production wells near the bottom of the pay zone. This method is preferable than the traditional gas injection process because it provides better sweep efficiency and utilizes the gravity force.

In this study, the effects of several reservoir/design parameters on the performance of GAGD process are investigated using numerical reservoir simulation means. These factors include reservoir dimension, oil viscosity, reservoir permeability, and well coordination. The results show that the investigated parameters have various degrees of influence on the performance of GAGD process.

Keywords: Gas Assisted Gravity Drainage, Improved Oil Recovery, Gas Injection.

1. Introduction[1]

The world is very thirsty for energy, and the demand for oil has been increasing constantly. There are still billion barrels of oil remaining trapped in the ground that is deemed unrecoverable using conventional methods of production. Therefore, oil companies are required to produce more oil by either IOR or finding new reservoirs which appears to be challenging since new discoveries are expected to occur in difficult environments. Therefore, the application of IOR processes utilizing new emerging technologies should be facilitated to effort this societal demand.

This work focuses on investigating the performance of an IOR gas injection technique called Gas Assisted Gravity Drainage (GAGD). One of the most important characteristics of GAGD process is that it works with the natural phenomenon of gravity segregation. The basic principle behind the GAGD

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process can be better explained by considering two fluids with different densities coexisting in a certain medium in which the heavier fluid sinks and the lighter fluid rises to the top due to natural gravity segregation.

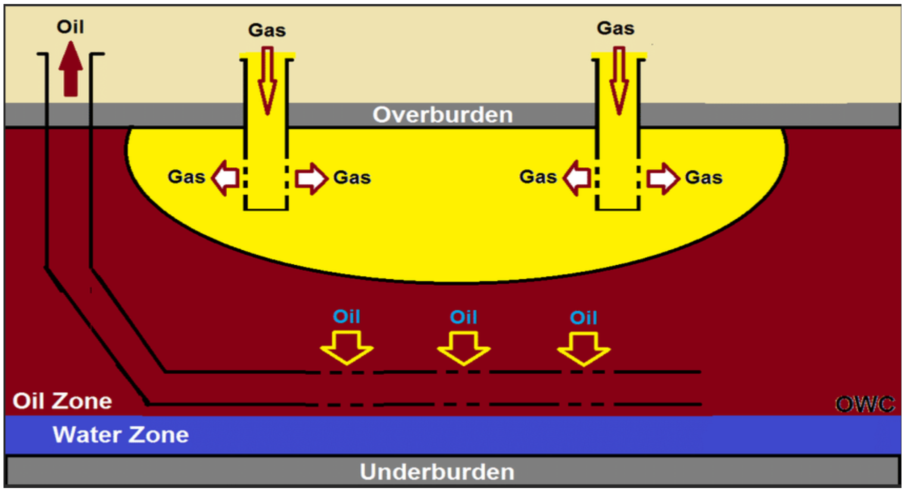

Figure-1: Conceptual diagram of GAGD

In GAGD process, gas is injected from the top of the pay zone and the drained oil would be produced from the bottom of the oil zone as shown in Figure 1 (Al-Mudhafar & Rao, 2018). Whether the reservoir is dipping or not, this process is expected to improve both the microscopic and the macroscopic sweep efficiencies. The performance of GAGD can be improved further by incorporating a horizontal production well.

Nitrogen (N_2) gas will be used as the injection gas in this study. Due to the density difference between Nitrogen and oil, the Nitrogen would drain the oil out of the porous media when injected in a gravity stable mode. Nitrogen is an inert, dry, non-toxic, and odorless gas; that has long been successfully used as the injection fluid for Enhanced Oil Recovery (EOR) applications and widely used in oil field operations for gas cycling, reservoir pressure maintenance, and gas lift. The costs and limitations on the availability of Natural gas and Carbon Dioxide (CO_2) have made Nitrogen an economic alternative for oil recovery projects (Al-Anazi, 2007). The Nitrogen gas is economically abundant, easy to obtain, and requires one eight the energy for its compression than that for an equivalent Natural gas volume (Arevalo-V, Samaniego-V, Lopez-C, & Urquieta-S, 1996). Depending on the injection rate, pressure, and location, the cost of Nitrogen gas can be as low as a quarter to a half that of Natural gas (Arevalo-V, Samaniego-V, Lopez-C, & Urquieta-S, 1996). Moreover, its ability to displace the oil and increase the reservoir pressure

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made it an ideal candidate for the GAGD process. It provides the lowest volume requirement for pressure maintenance and it is usually cheaper than CO_2 or a hydrocarbon derived gas for displacement in EOR applications and has the added benefit of being non-corrosive (Al-Anazi, 2007). The injected Nitrogen does not react with the reservoir fluids to produce undesirable by-products and precipitates (Islam, Alshehhi, & Ohadi, 2009).

2. Objective

The objective of this study is to investigate the effects of several parameters on the performance of GAGD process. These parameters include: oil viscosity (μo), lateral extension of project area (L), width of project area (W), thickness of the project volume (H), vertical to horizontal permeability ratio (kz/kx), injection well penetration distance (C), injection well location (α), production well length (B), production well placement (A), producer well location (β), distance between the two horizontal producers (D),gas injection rate (Q_g), and the injection gas density (ρ_g).

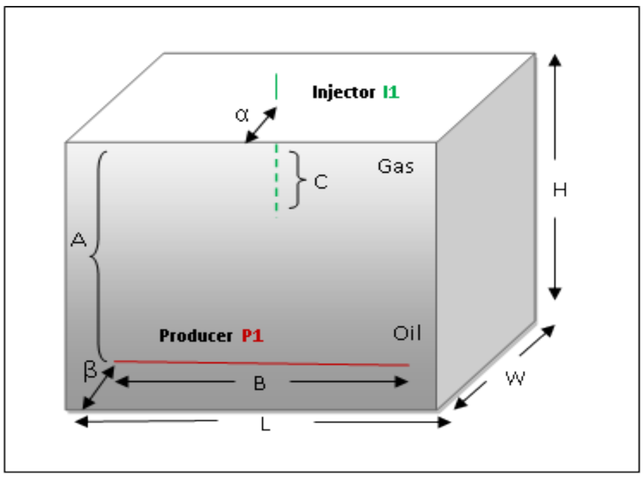

Figure-2: Schematic of the reservoir design parameters.

3. Methodology

In order to achieve the proposed objectives, a 31x31x31 Cartesian model representing typical oil reservoir was built with the selected fluid and rock properties using a fine grid simulation tool (Eclipse-100).

Oil-gas fluid system was described as a black oil and pseudo gas. The properties of the oil were assigned to represent a typical standard reservoir, and the properties of the gas were selected to mimic

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Nitrogen gas (N_2) behavior under different pressure and temperature as shown in tables below. After constructing the simulation model, a grid sensitivity study was performed to highlight the optimum number of grid blocks.

Table-1: Reservoir and fluid properties

Reservoir pressure, psi	4000	Reservoir porosity, %	15
Reservoir temperature, ^{o}F	180	Depth, ft	10,000
Lateral reservoir permeability, md	100	Oil saturation (in oil zone), %	80
Vertical reservoir permeability, md	10	Water saturation, %	20
Reservoir length, ft	427.8	Initial Rs, Mscf/STB	1.15
Reservoir width, ft	427.8	Oil density, Ibm/ft^3	53
Reservoir height, ft	80.6	Oil viscosity, cp	1

Table-2: Nitrogen gas data

P (psi)	Z factor	Bg (rbbl/Mscf)	Viscosity (cp)
400	1.005	8.0970	0.0207
1200	1.028	2.7610	0.0216
2400	1.061	1.4256	0.0234
4400	1.160	0.8495	0.027

The vertical injection well is placed in the center of the model, and a horizontal producer at the bottom of the reservoir as shown in Figure-3.

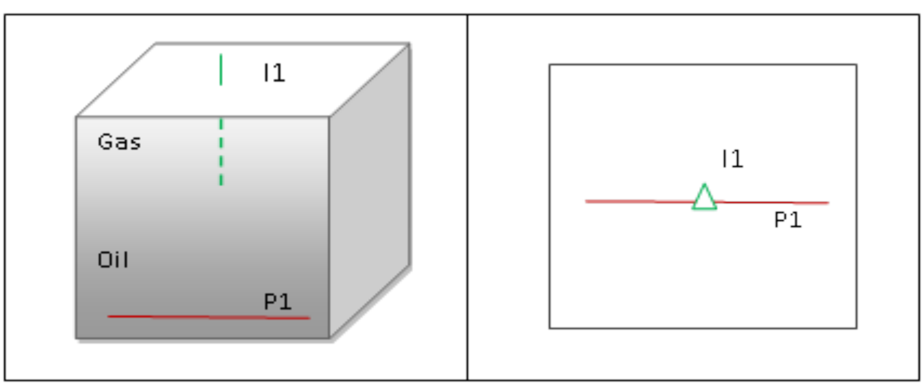

Figure-3: 3D and top view of the reservoir with vertical injector and horizontal producer.

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After building the simulation model, a sensitivity study was done by changing each parameter separately with all other design parameters fixed. Table-3 shows the sensitivity runs for each parameter.

Table-3: Summary of Conducted Numerical Runs.

Runs	Investigated Parameter	Range
1-5	Grid number in x, y, z directions	31 – 71 grids
6-8	Oil viscosity (μ_o)	0.1 – 100 cp
9-11	Reservoir length (L)	(0.25 – 1.5) L
12-14	Reservoir width (W)	(0.25 – 1.5) W
15-17	Reservoir thickness (H)	(0.25 – 3.7) H
18-20	Reservoir permeability ratio (Kz/Kx)	0.01 - 1
21-23	Injection well penetration distance (C)	(0.6 - 3) C
24-26	Location of injection well (α) (Shifted distance from the center)	(0 - 0.94) α
27-29	Horizontal Production well Length (B)	(0.5 – 2) B
30-32	Horizontal Production well placement location (A)	(0.3 – 1) A
33-35	Location of injection well (β) (Shifted distance from the center)	(0 - 0.9) β
36-38	Distance between two horizontal production wells (D)	(0.6 – 1.8) D
39-42	Gas injection rate	(0.1 – 0.6) PV
43-46	Injected gas density	12.8 - 13.9 lbm/ft^3

The results were then recorded, analyzed and the different cases were compared. The oil recovery factor was obtained from each run in order to evaluate the effect of investigated parameters on the performance of the GAGD process

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4. Results and Discussion

Grid Number Sensitivity

The effect of the gridding system on the performance of GAGD process was investigated to find the optimum number and size of grid blocks where the numerical dispersion effect is minimum. The Model grid number was built with 31x31x31grids as a base case. After that, four runs were conducted with different grid numbers and sizes as shown in table 4.

Table-4: Gridding system

Runs	Number of Grids			Grid size		
	N_x	N_y	N_z	ΔX	ΔY	ΔZ
Run 1	31	31	31	13.8	13.8	2.6
Run 2	41	41	31	10.4	10.4	2.6
Run 3	51	51	31	8.4	8.4	2.6
Run 4	61	61	31	7.0	7.0	2.6
Run 5	71	71	31	6.0	6.0	2.6

Figure-4 shows the oil recovery versus pore volume of gas injected (PVI) for the different grid numbers and sizes. The gridding has a negligible effect on the oil recovery.

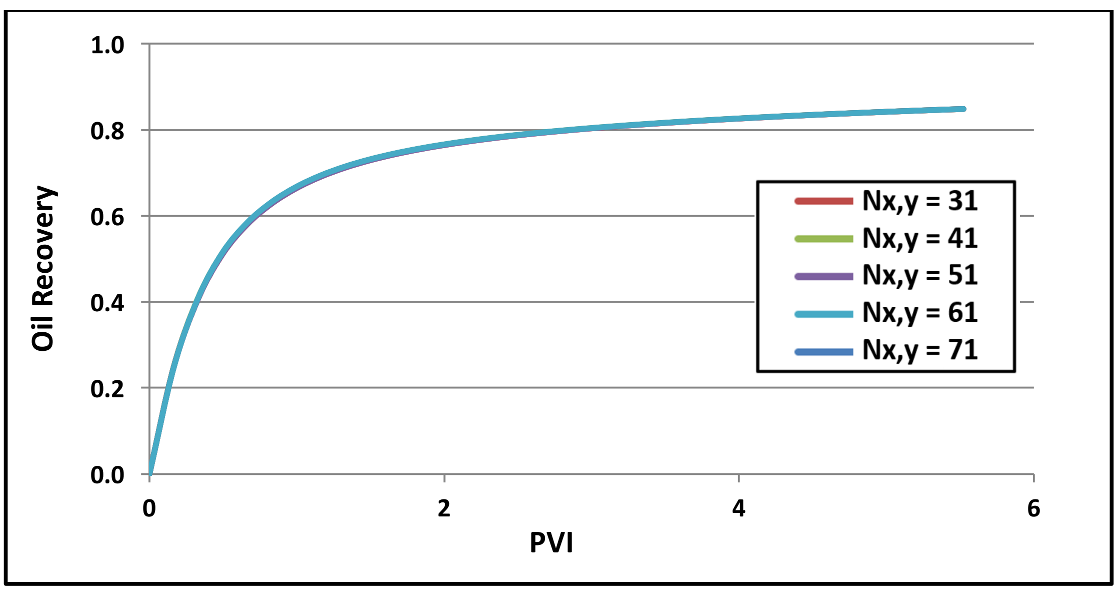

Figure-1: Oil recovery at different grid numbers.

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The smallest grid number and size was chosen as a base case for the sensitivity studies for simplicity and to save time on the runs conducted.

Effect of Oil Viscosity on Oil Recovery

The investigation of the effect of reservoir oil viscosity (μ_o) on the GAGD performance was conducted by changing the viscosity from 0.1 to 100 cp and the oil recovery was recorded versus the pore volume of gas injected at the different viscosity values.

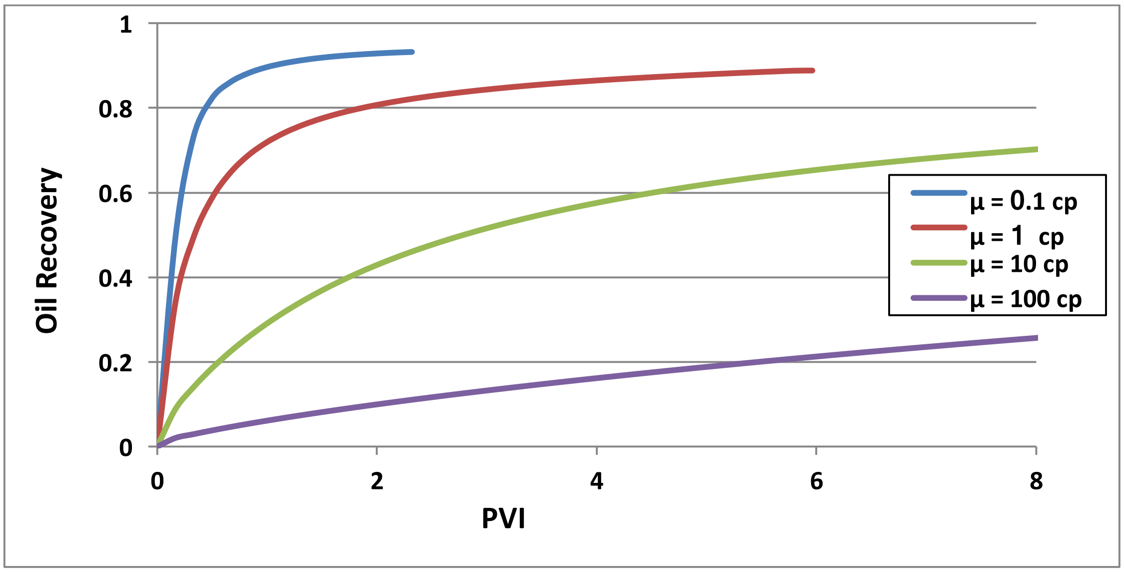

Figure-5: Oil Recovery at different oil viscosities.

Figure 5 shows that the lower the viscosity, the higher the oil recovery for a fixed PVI. Previous research shows that the GAGD process is applicable for heavy oil reservoir where secondary immiscible oil recovery was 64% IOIP (Sharma Amit, & RaoDandina, 2008). This investigation proves the previous research result for the ability of applying the GAGD in higher viscosity reservoir (100 cp) but with lower recovery than the lighter oil as expected.

Effect of Reservoir Dimensions on Oil Recovery

The modeled reservoir dimensions: Length (L), width (W) and thickness (H), effect on the performance of the GAGD process was investigated. The length and width of the reservoir were set initially to 426 ft and then changed separately from 0.25 L to 1.5 L and from 0.25 W to 1.5 W to study its effect on the performance of GAGD process.

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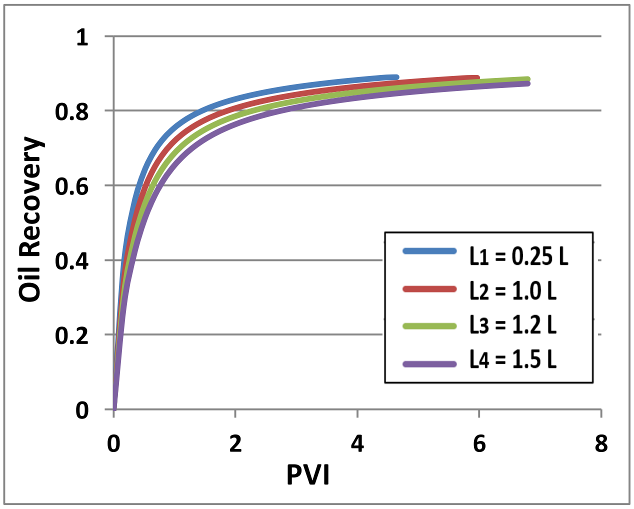

Figure-6: Oil Recovery at different reservoir length values.

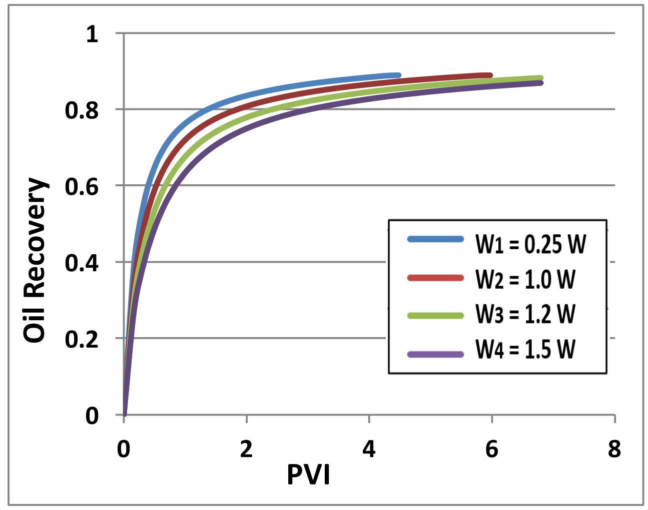

Figure-7: Oil Recovery at different reservoir width values.

Figure 6 and Figure 7 show that the oil recovery increases as the reservoir becomes smaller. The fixed gas injection rate makes the extracting of oil from smaller areas much easier than the bigger one because of the higher areal sweep efficiency; percentage of the area recovered by the injected gas over the total area, in smaller reservoir.

Reservoir thickness (H) is one of the important parameters in this investigation study. Figure 8 shows that the GAGD process will provide lower oil recovery in a case of a very thick reservoir in which the effect of the supplied energy by gas injection and the gas oil segregation by the gravity takes very long time. However, this low recovery is noticeable also at very thin reservoir because of the fast gas breakthrough and high gas production.

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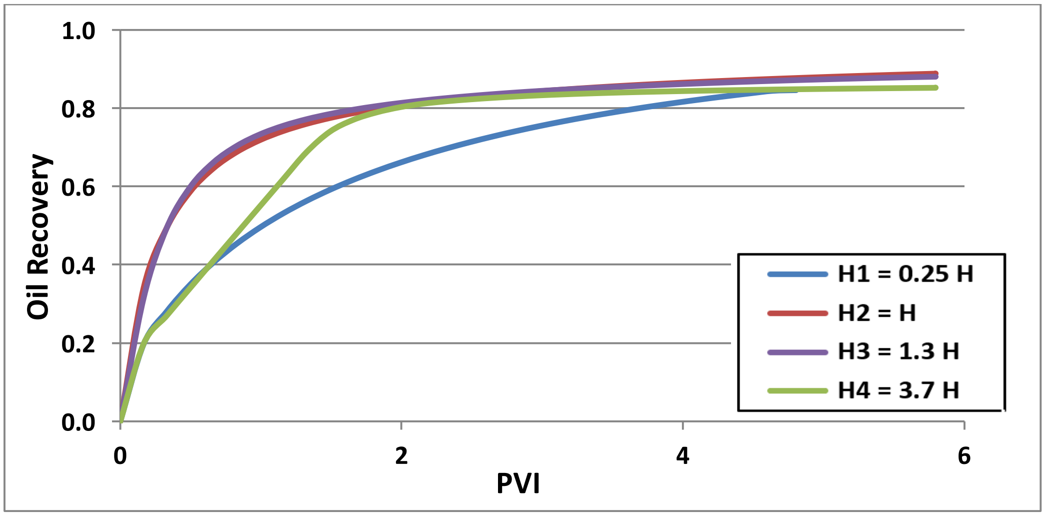

Figure-8: Oil Recovery at different reservoir thicknesses.

Effect of Reservoir Permeability Ratio (Kz/Kx) on Oil Recovery

Reservoir heterogeneity has a great influence in most IOR processes. Initially the vertical to horizontal reservoir permeability ratio was set to be 0.1 (vertical permeability is 10% of the horizontal permeability) for the base case with equal horizontal permeability in the x and y directions. This ratio was changed to lower and higher values from 0.01 to 1 to investigate its effect on the performance of the GAGD. Figure 9 shows that when the permeability ratio was set to a small value, the field had lower oil recovery than the other values at low PVI for a certain limit and the increase of the permeability ratio above 0.1 has an insignificant effect on the oil recovery. However, at high PVI, higher oil recovery is obtained from lower permeability ratio.

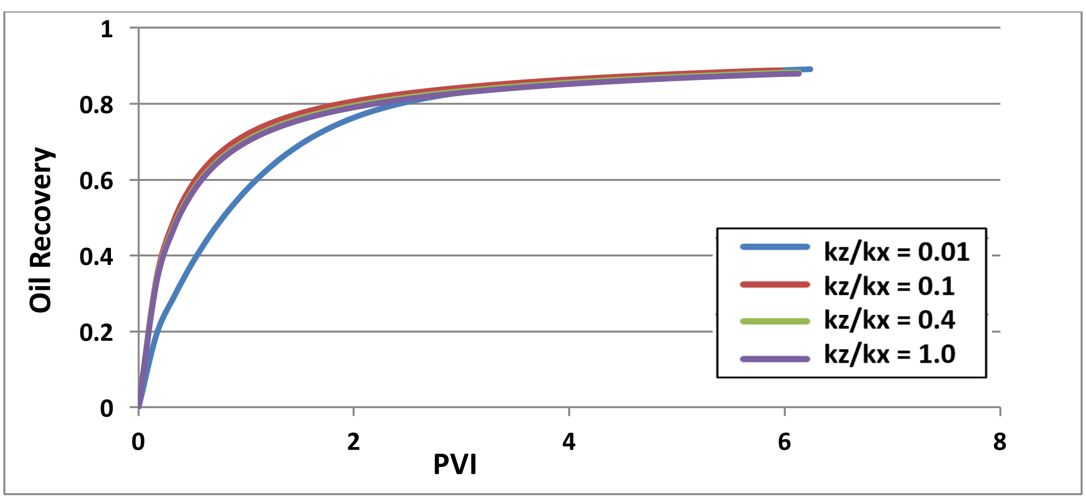

Figure-9: Oil Recovery at different reservoir permeability ratios (Kz/Kx).

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In previous laboratory investigations, different kz/kx ratios have been created by varying the glass beads sizes. It was found that a lower kz/kx will result in a slightly higher recovery (64.73% ROIP) in heterogeneous reservoir due to the higher dominance of vertical permeability. After that, investigations have been done by using ECLIPSE software, and the results show that for heterogeneous model, lower kz/kx will yield a higher FOE (Islam, Alshehhi, & Ohadi, 2009) as shown in Figure 10.

Figure 11 shows oil recovery versus pore volume of gas injected in larger scale to clarify the effect of the investigated parameter. The trend of the lowest permeability ratio in this study can be considered similar to the one from the previous research. However, the result does not show a large variation in the recovery factor with permeability ratio change. The difference in the results may depend on reservoir properties and conditions.

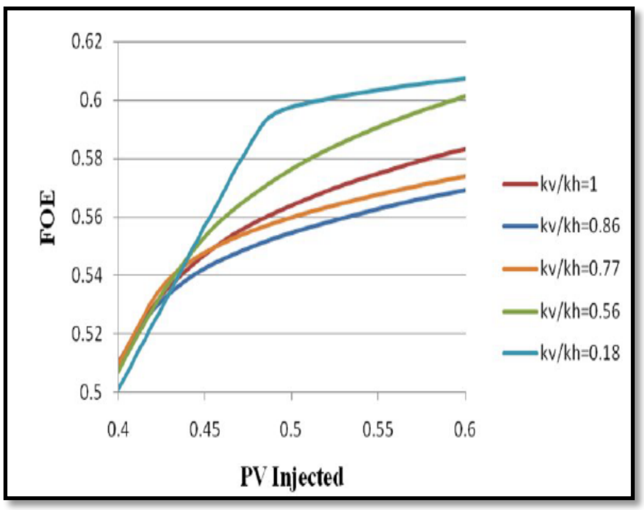

Figure-10: Oil recovery vs. injected pore volume from previous research

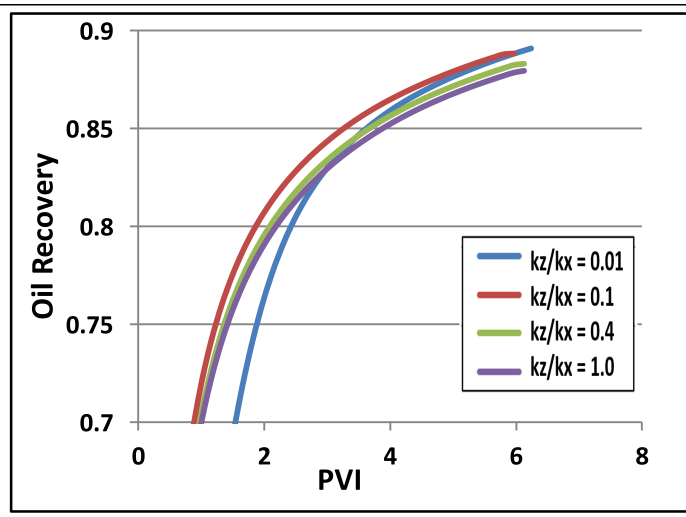

Figure-11: Oil Recovery at different reservoir permeability ratios (large scale).

Effect of Injection Well Penetration Distance on Oil Recovery

The injection well is primarily located at the center of the reservoir model and extended from the top of the reservoir to the first three layers (C = 7.8 ft from the top of the reservoir). The penetration distance was changed from 0.6 C to 3 C from the top of the reservoir to study its effect on the performance of GAGD process.

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Figure 12 shows that the injection well penetration distances in case of vertical injector have no effect on the oil recovery. This could be due to the fixed gas injection rate. However, the distance between the injector and the producer should be high enough to delay the gas break through.

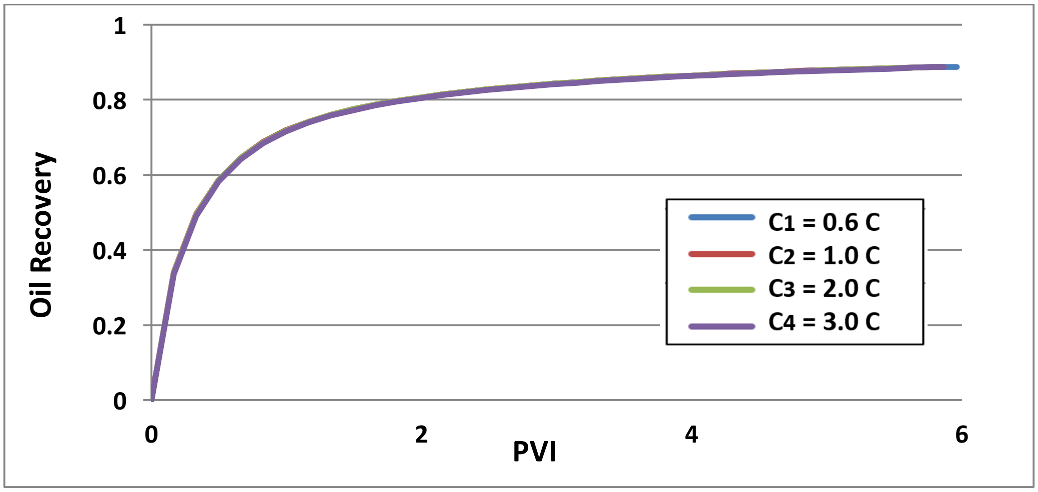

Figure-12: Oil Recovery at different vertical injection well penetration distance values.

Effect of Location of Injection Well on Oil Recovery

The vertical injection well was moved from its initial location (at the center) to study the effect of well alignment on the performance of GAGD process by analyzing the field oil recovery at the different well locations. Figure 13 shows that changing well location with fixed injection rate, penetration distance and fixed distance between the injection and the production wells will not affect the oil recovery especially in case of small reservoirs.

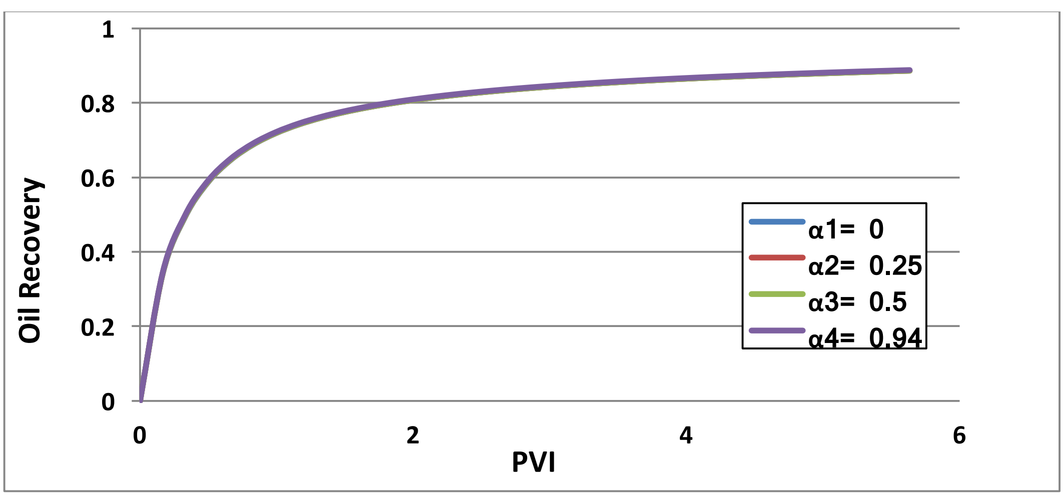

Figure-13: Oil Recovery at different injection well locations.

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Effect of Horizontal Production Well Length on Oil Recovery

Studying the design parameters of the horizontal well is one of the main objectives of this work. The horizontal production well length (B) was studied in a range from 0.5 B to 2 B at fixed reservoir fluid and rock properties, gas properties, gas injection rate, and injection well design. The oil recovery was analyzed at different length values to investigate its effect on the GAGD process.

Figure 14 shows that increasing the length of the horizontal production well has a very small effect on the oil recovery in respect to the injected pore volume. The reason behind these insignificant effects could be due to fixed injection rate, In other words, due to a fixed supply of energy. However, it could show a larger oil recovery with time for the longer wells.

Sometimes the extra extension of the horizontal well is useless if the energy supply by the gas injection does not reach that part. Moreover, it could also prove uneconomical when incremental production does not cover the increase in the cost for the longer well.

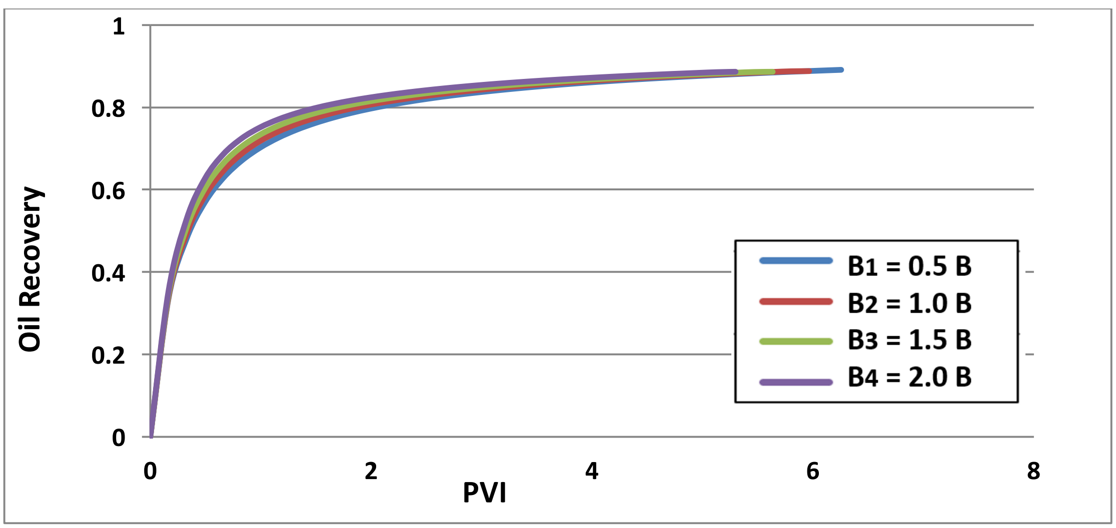

Figure-14: Oil Recovery at different horizontal production well lengths.

Effect of Horizontal Well Placement on Oil Recovery

The distance between the injection and the horizontal production wells is one of the most important parameters that affect the performance of the GAGD Process because it impacts the gas oil segregation time as well as the gas break through time.

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The horizontal production well placement was changed from being very shallow and close to the injector to being at the bottom of reservoir. Figure 15 shows the relation between the oil recovery and the pore volume of gas injected at different horizontal well placement in the range from 0.3A to A. The results show that placing the horizontal production well at a high depth and locating it at the bottom of the production zone will provide the necessary time for gas oil segregation and delay the gas break through which surely will result in higher oil recovery.

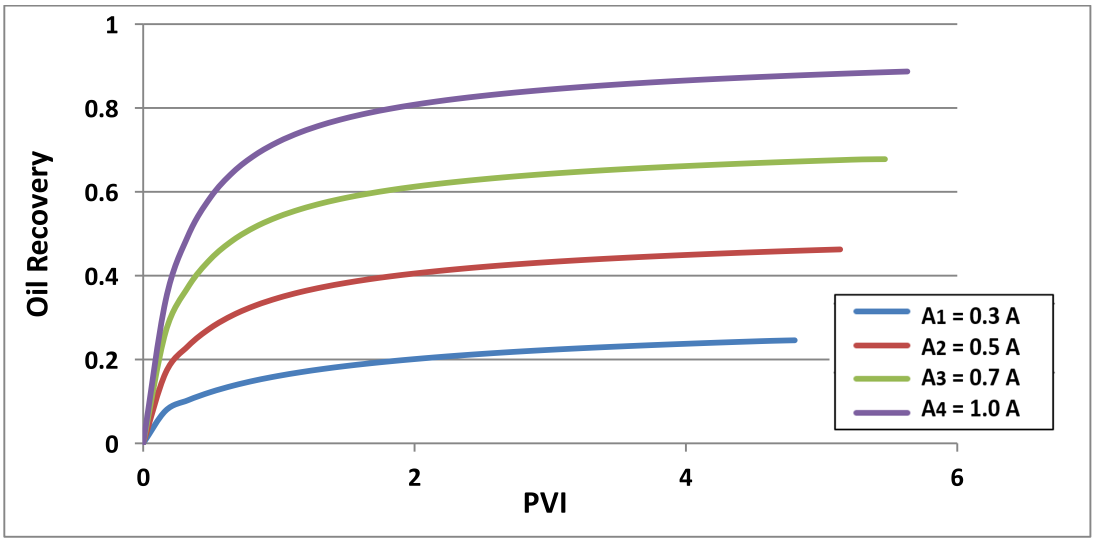

Figure-15: Oil Recovery at different horizontal production well depths.

Effect of Location of Horizontal Production Well on Oil Recovery

While building the base case model, a horizontal producer was located at the bottom of the reservoir and directly below the vertical injection well. After that, the horizontal producer was shifted from the center to study the effect of production well alignment on the performance of the GAGD process.

Figure 16 shows that higher recovery is obtained when the horizontal producer was located at the middle of the reservoir (well alignment β=0) directly under the injection well. When the well is moved away from the center, the oil recovery becomes lower at fixed PVI because it will need larger injected pore volume to deliver the gas energy to the oil near these wells and to get the same recovery as the one obtained in the closer one.

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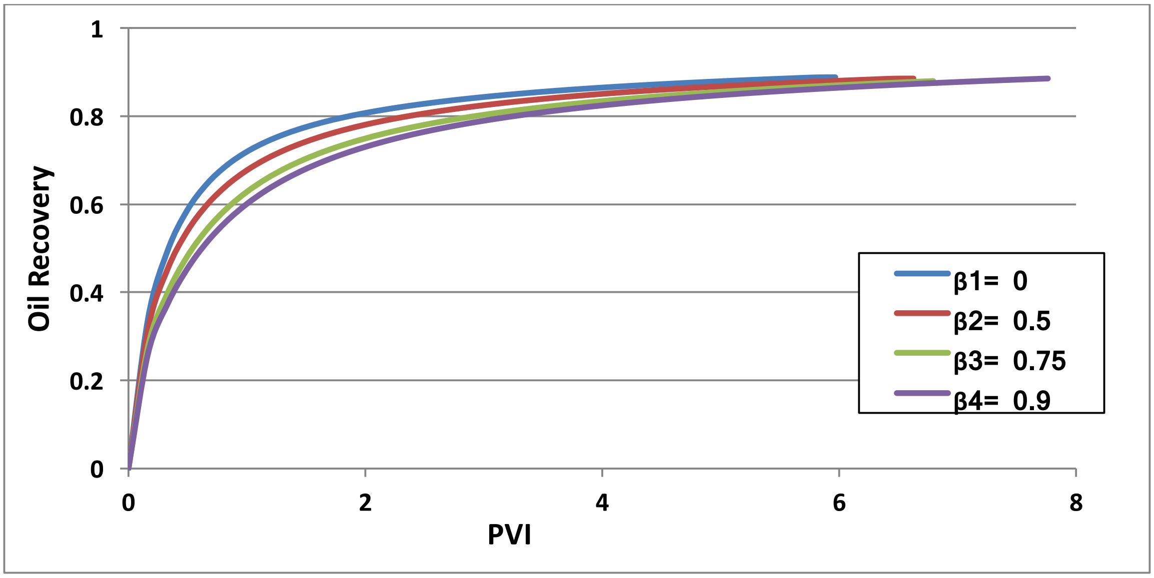

Figure-16: Oil Recovery at different horizontal production well locations.

Effect of Distance Between Two Horizontal Production Wells on Oil Recovery

In this case, a production well was added to the model to have two horizontal producers. The effect of the horizontal production well number was not investigated because it totally depends on the economics where the cost of drilling a new well should be considered and the net present value (profits) should be calculated. This work has no economic analysis. However, the second well was added to study the effect of the distance between the horizontal producers on this process.

Figure 17 shows that the larger the distance between the two horizontal producers, the lower oil recovery because of the time needed for the gas to reach these wells. However, decreasing the distance between the production wells after a certain limit will not add value. Therefore, the best case in our modeled reservoir is locating the wells at equal distance away from the center in the middle of the reservoir.

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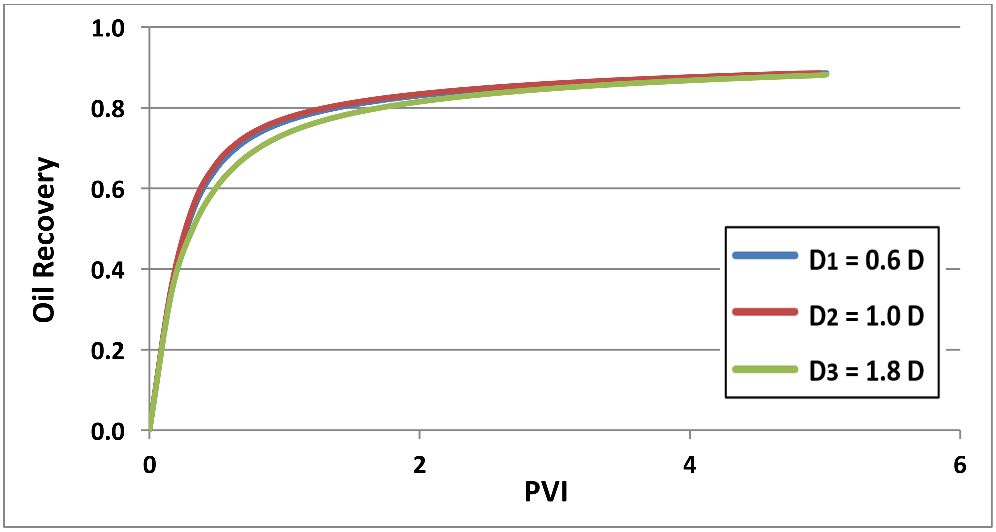

Figure-17: Oil Recovery at different distance between the horizontal producers.

Effect of Gas Injection Rate on Oil Recovery

Gas injection rate is the main factor that controls any gas injection IOR process. In this research, the gas injection rate was initially set to be 10% of the reservoir pore volume per year. It was increased gradually to reach 60% of the pore volume to study its effect on the application of GAGD process.

The dimensionless plot (Figure 18) proves that high injection rate will cause faster gas break through which will result in lower sweep efficiency and high gas production. This will provide lower oil recovery than the relatively low injection rate at fixed injected pore volume.

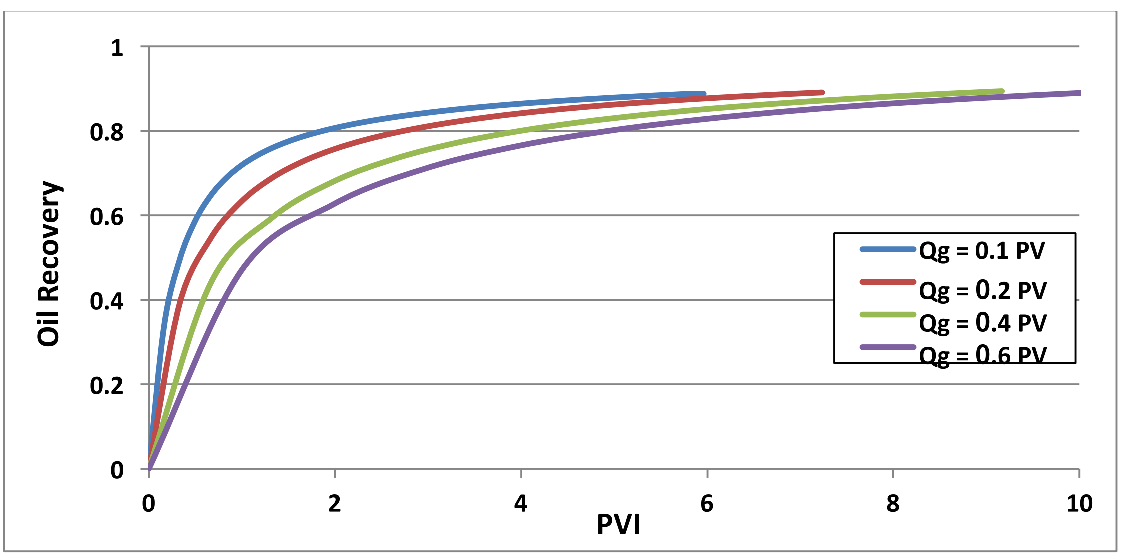

Figure-18: Oil Recovery vs. injection pore volume at different gas injection rates.

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When plotting the oil recovery against the time as shown in Figure 19, it shows that the higher the injection rate is the higher the oil recovery and the shorter the time up to a certain limit, which supports the previous investigation study results that shown in Figure 20 (Sharma Amit, & RaoDandina, 2008). However, the plot of the oil recovery with respect to injection pore volume shows that this faster and higher result will need a larger gas volume. The economic study would help choosing the optimum gas injection rate.

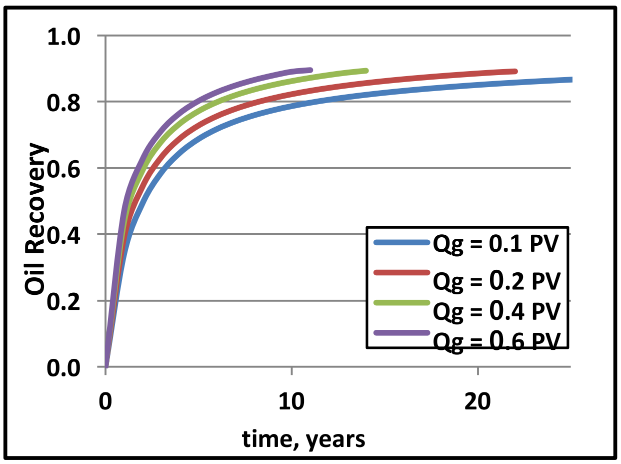

Figure-19: Oil recovery vs. time at different injection rate.

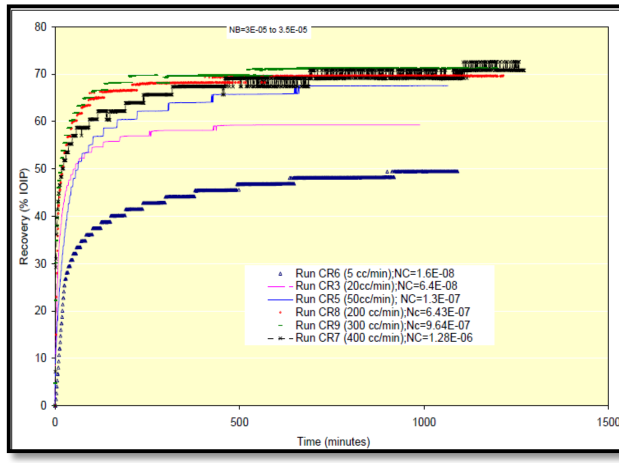

Figure-20: Oil recovery obtained at different gas injection rates from previous research.

Effect of Injection Gas Density on Oil Recovery

The effect of gas properties was investigated by changing the injected gas density. The gas density was varied by changing the gas temperature and pressure using commercial software called PEACE SOFTWARE. The density was changed from 12.8 – 15.1 lbm/ft3 to investigate its effect on the performance of GAGD process.

Figure 21 shows the oil recovery versus the PVI at different gas densities. It is obvious that gas density has insignificant impact on oil recovery. A possible reason for this is due to the small range of gas density variation used in this investigation.

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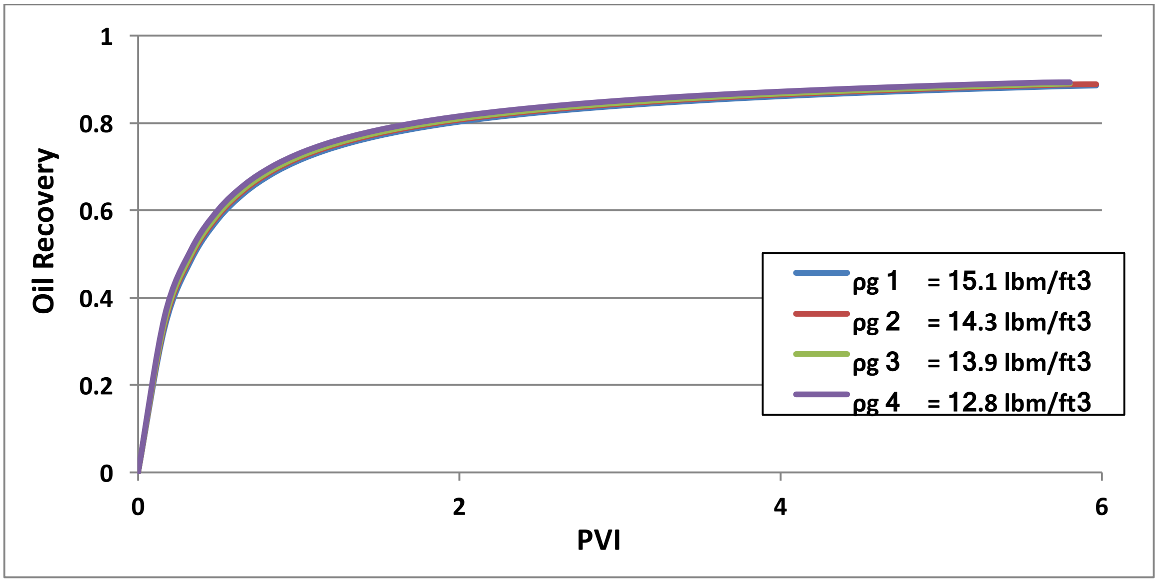

Figure-21: Oil Recovery at different gas densities

Injection well type Sensitivity

The gas injection well was changed from vertical to horizontal well and the sensitivity analysis for all parameters was repeated. Figure 22 shows a schematic of this case both in 3D and top view.

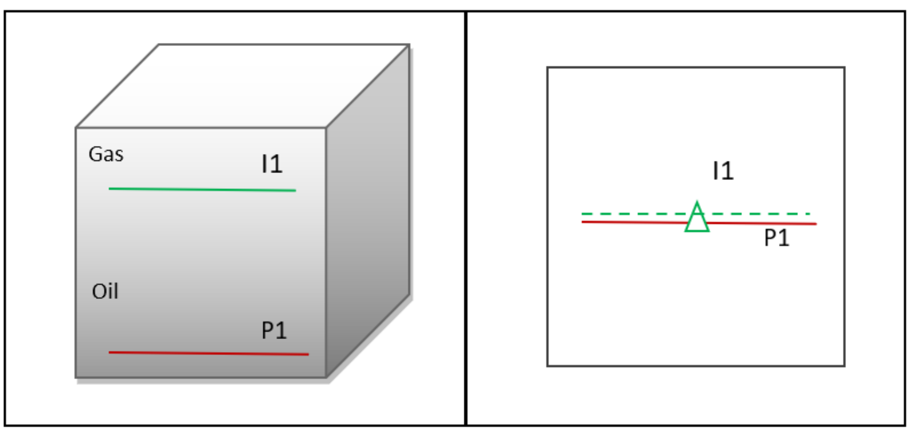

Figure-22: 3D and top view of the reservoir with horizontal injector and horizontal producer.

The results show that at a constant injection rate, the injection well architecture has an insignificant effect on the performance of GAGD process.

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5. Conclusion

1. The effect of grid numbers in the described reservoir model was negligible, and hence a small grid number (31x31x31) was used to reduce the run time.
2. The GAGD process provides better results in light oil, but it is applicable at higher oil viscosity (100 cp).
3. The density of the injected gas has no effect on the oil recovery. However, the gas injection rate has an obvious effect on the process, and it should be selected based on the economic study and the break-through time.
4. The heterogeneity of the reservoir has a small effect on the oil recovery and therefore the lower (Kv/Kh) will more likely provide better oil recovery.
5. The reservoir dimensions: length, width, and thickness, also have a small effect on the oil recovery. At constant injection rate, the smaller the reservoir the higher the oil recovery and the larger the thickness than a certain limit the smaller the oil recovery.
6. The length of either the injector or the producer has an insignificant effect on the oil recovery. However, the horizontal production wells will provide a higher recovery rate when the production wells are located at the middle of the reservoir with equal distance from the center. Moving the wells closer did not affect the results but locating it on the edges of the reservoir (i.e. large distance between the wells) decreases the oil recovery because of the time and the energy needed for the gas to move to these wells.
7. In the case of having a single horizontal production well, higher oil recovery was gained when the well is located directly under the injection well with maximum separation distance (i.e. at the bottom of the reservoir).
8. Comparing the different injection well architecture cases, the results show that at a constant injection rate, the injection well architecture has an insignificant effect on the performance of GAGD process. Therefore, the vertical well should be selected from an economical perspective.

9. Nomenclature

GAGD = Gas Assisted Gravity Drainage

IOR = Improved Oil Recovery

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EOR	= Enhanced Oil Recovery
IOIP	= Initial Oil in Place
ROIP	= Recoverable Oil in Place
Kx	= Lateral permeability in x direction, md
Kz	= Vertical permeability, md
R_s	= Dissolved gas ratio, Mscf/bbl
B_o	= Oil formation volume factor, bbl/STB
B_g	= Gas formation volume factor, bbl/MSCF
B_w	= Water formation volume factor, bbl/STB
Z	= Compressibility factor
μ_o	= Oil viscosity, cp
μ_g	= Gas viscosity, cp
S	= Coordinates x, y, and z
Ns	= Number of grid block in S direction
ΔS	= Size of the grid blocks along S direction, ft
L	= Reservoir length, ft
FOE	= Field Oil Efficiency
PVI	= Pore volume injected
α	= Alignment of the vertical injector; distance from the center
β	= Alignment of the horizontal producer; distance from the center
A	= Production well length for the base case, ft
B	= Production well placement for the base case, ft
C	= Injection well penetration distance for the base case, ft
D	= Distance between the two horizontal production wells for the base case, ft

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