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Simulation Study of Enhanced Condensate Recovery in a Gas-Condensate Reservoir

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Abstract

In gas condensate reservoirs, by reservoir depletion, pressure decreases below the dew point pressure of the fluid and condensate forms in the reservoir. This heavy part of the gas has found many applications in industry and also in daily life. When condensate drops out in the reservoir not only is this valuable liquid lost, but also its accumulation results in forming a condensate bank near the wellbore region. The created bank makes a considerable reduction in gas well productivity. These facts demonstrate that finding an economical way to increase the condensate recovery from condensate reservoirs is essential.

In this study gas injection has been simulated in a gas condensate reservoir to increase the condensate recovery factor. In addition, capability of injection of different types of gas in condensate recovery has been compared through different injection schemes. The injection schemes that have been considered are: different injection rates, different reservoir pressures at which the injection is implemented and different injection durations.

A compositional simulator was applied to simulate a simplified gas condensate reservoir model. The injection pattern was a one-eighth of a five-spot pattern with finer grids near the producer and injector. The simulation results showed an increase in condensate recovery from 5% to 30% in all injection cases.

Many parameters can affect the decision of selecting the injection scheme, other than the gas and condensate recovery factor. Therefore, an economical evaluation and analysis is inevitable to take them all into account to determine the optimum scheme.

Keywords: *Enhanced Condensate Recovery, Gas Condensate Reservoirs, Gas Recycling, Reservoir Simulation, Condensate Drop-Out*

1- Introduction

In gas-condensate reservoirs gas injection is an operation applied to reduce the condensate drop-out in the reservoir. Condensate is formed from valuable heavy components of hydrocarbon mixtures. Accumulation of condensate in a reservoir can cause a reduction in gas permeability and result in decreasing gas well productivity [1]. However, according to the research, gas–condensate relative permeability varies with production rate at near wellbore condition[1].

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The flow in this region is controlled by the complex interaction of capillary, viscous and inertial forces [2]. At low condensate saturations the relative permeability values decrease when the flow rate increases, due to the dominance of the inertial effect. However, the positive coupling effect surpassed the inertial effect at higher condensate saturation, resulting in a net increase of relative permeability with rate [3,4].

Injection can be implemented at the initial reservoir pressure to maintain the pressure above the dew point (full pressure maintenance), or after the reservoir pressure falls below the dew point pressure (partial pressure maintenance) [5], in which injected gas re-vaporizes the condensate and reduces condensate accumulation in the reservoir.

Gas cycling has been implemented in gas condensate reservoirs for many years, but due to more applications and the value of natural gas, engineers were forced to find an appropriate replacement for it in the injection process. N_2 and CO_2 were suggested as two alternatives which are now applied in some reservoirs [6, 7]. As N_2 is an available and a non-corrosive gas, it is a good alternative and can be properly applied for this purpose. Injection of these gases into the reservoir vaporizes condensate and increases the reservoir fluid dew-point pressure. The contact of the injected gas with the condensate leads to enrichment of the gas due to mass transfer [8].

This study compares the efficiency of injection of different gases of N_2, CO_2, and CH_4 and also gas cycling for condensate recovery from a gas condensate reservoir. For this work a compositional simulator has been applied and different injection schemes have been simulated. In these schemes the effect of changing the injection rate, injection pressure and injection duration on recovery have been investigated. The appropriate and optimum case can be selected considering the results of the simulation work and performing an economical analysis. In this case, all the affecting parameters such as the price of the gas and condensate, the price of the injection gases and the cost of the facilities needed in each scheme for each pressure level should be considered.

2- Model description

In order to simulate the model, a simplified gas-condensate reservoir model has been applied. The reservoir specifications and fluid properties have been tabulated in Tables 1-3.

Table 1. Reservoir properties

Layer	k_h (md)	k_v (md)	Thickness (ft)	Initial pressure (psia)	5248
1	130	13	30	Reservoir temperature (F)	219
2	40	4	30	Porosity	0.13
3	20	2	50	PV compressibility (psi^{-1})	4.00E-06
4	150	15	50	water compressibility (psi^{-1})	3.00E-06

A three dimensional model of one-eighth of a five-spot pattern has been considered to simulate the injection pattern. Due to the symmetrical form of the five-spot injection pattern one-eighth of it has been considered, which makes the simulation run time program remarkably shorter [9]. A schematic of this model has been shown in Fig. 1.

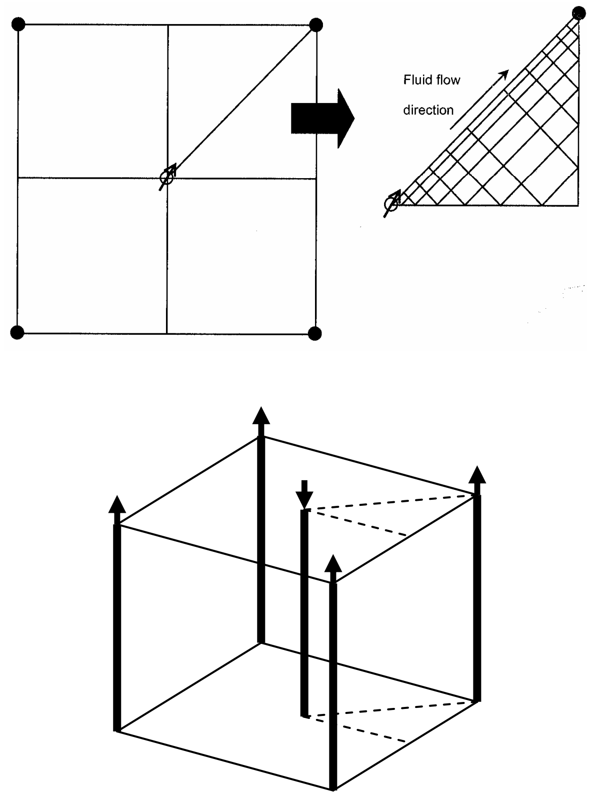

Figure1. Schematic of one eighth of a five spot injection pattern [6]

The constructed reservoir model (in CMG model builder module) is one-eighth of a 31×31×4 grid, with the dimensions of 2903.5 (ft) in I and J directions, and 110(ft) in K direction, which has been shown in Fig. 2. One injector and one producer are located in the corners of the grid. Smaller grids are made near the injector and producer in order to model the fluid flow more accurately. As the blocks located in the border of the simulation grid are smaller than that of the described model, their porosity and transmissibility have been reduced to half, quarter and one eighth of their initial size according to their location.

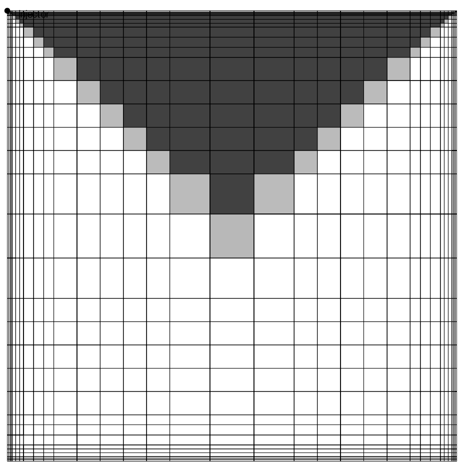

Figure 2. Simulation model constructed in CMG model builder

3- Results and discussion

Based on the aim of the study, different runs have been implemented on the simulated model. In this model the third and the forth layers are opened to production, and injection is performed through the first and the second layers.

Production period is 15 years and the maximum rate of the production is 2.4 MMSCF/D, which has been set as the first constraint. The second constraint is the minimum bottom-hole pressure which is equal to 500 psia.

Firstly, reservoir behavior by natural depletion was investigated. Reservoir pressure and average condensate saturation in the reservoir during this period have been shown in Fig. 3 and Fig. 4, respectively.

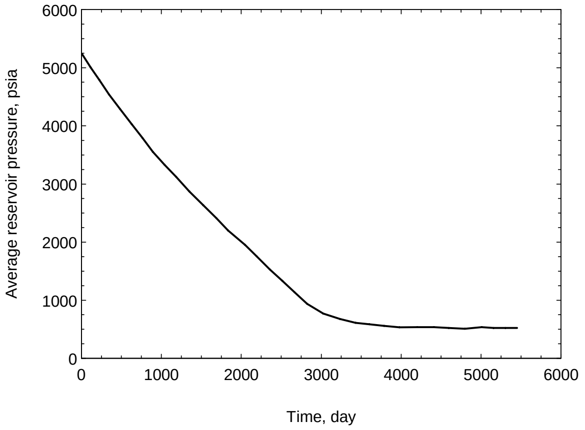

Figure 3. Average reservoir pressure during natural depletion period

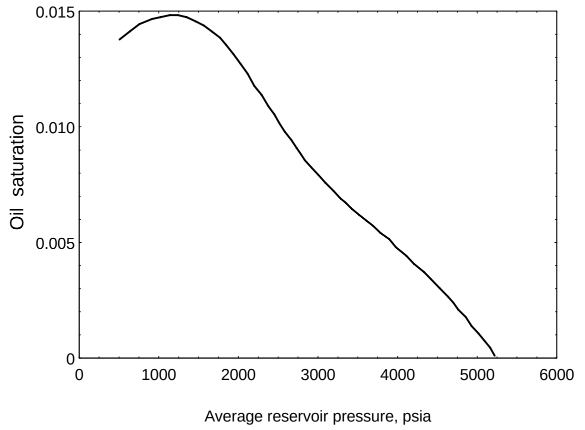

Figure 4. Average condensate saturation during natural depletion period

3.1- Effect of injection gas type

In this section, the effects of three injection gases and gas cycling with different rates have been investigated. Composition of the recycled gas is given in Table 1. Injection was implemented at the initial reservoir pressure.

As can be observed from Fig. 5, when the injection rate is equal to the production rate, the performance of CO_2 and CH_4 in condensate recovery is almost the same. They make an increase of about 24% compared to the base case (no injection case)

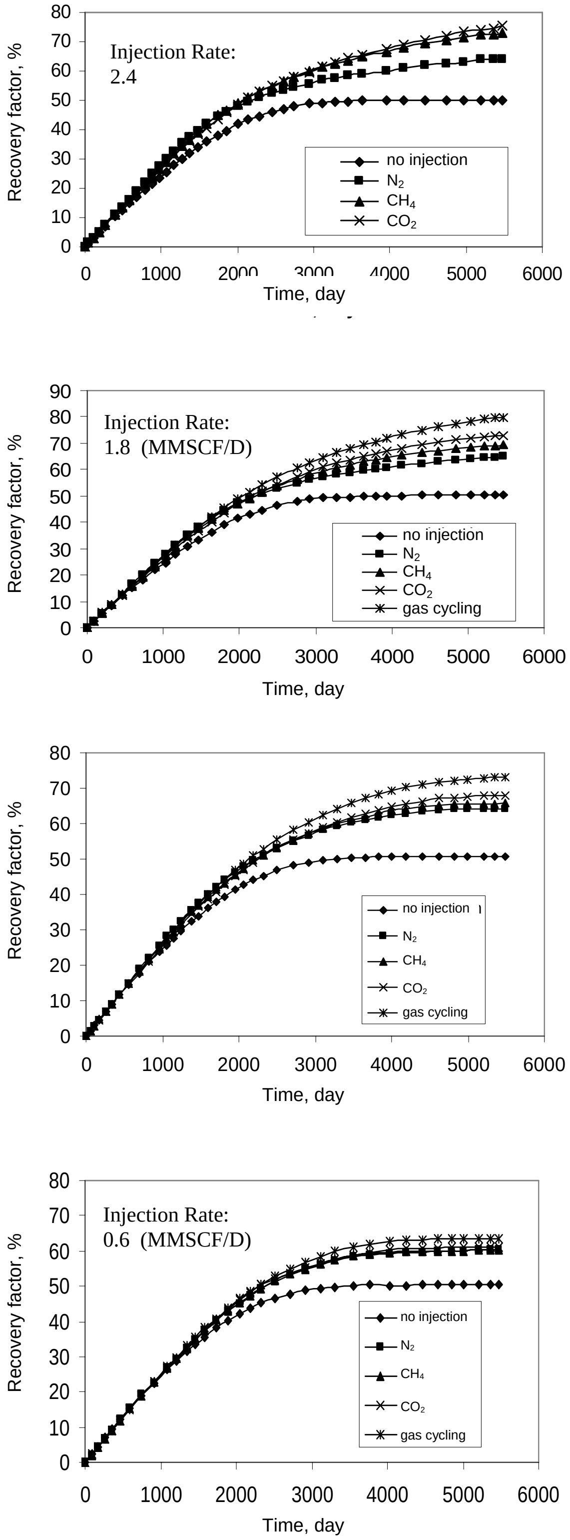

Figure 5. Comparison of condensate recovery of different injection gases in different cases of injection rate at initial reservoir pressure

in which condensate recovery is about 50%, whereas N_2 can only make an increase of about 15% [10]. According to the previous studies, the addition of some nitrogen causes a considerable increase in mixture dew-point pressure. This dew-point eventually becomes much higher than the reservoir pressure. Depending on the level of mixing and dispersion, liquid drop out occurs, thus the efficiency of the process is reduced [11]. This fact can be observed from Fig. 6 in which the phase envelope of the fluids resulted from mixing N_2, CO_2 , and CH_4 with the reservoir fluid has been compared. Gas cycling with a rate equal to the production rate was excluded.

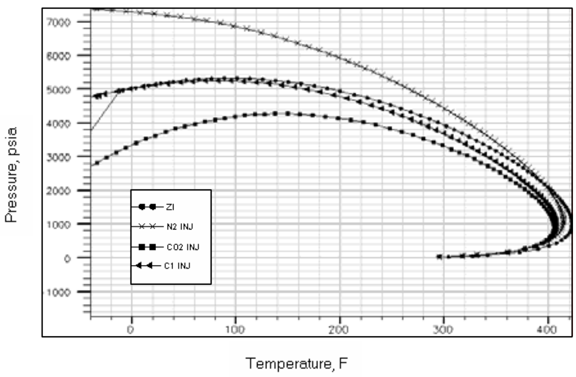

Figure 6. Comparison of phase envelope resulted from mixing different injection gases with the reservoir fluid

High injection rate results in the early breakthrough of the injection gases and reduces the ultimate gas recovery to a very low value. Recovery of gas and condensate for all the injection cases has been given in Tables 2 through 5.

For the other injection rates, gas cycling is the most effective way to increase the condensate recovery. When the injection rate is 75% of the production rate (1.8 MMSCF/D), the recovery by gas cycling is about 80%, while by CO_2, CH_4 and N_2 injection, recoveries are 73%, 70%, and 65% respectively. Based on the experiments and studies done before, N_2 injection is not as effective as CH_4 and CO_2, as it causes higher liquid drop out, and has lower evaporating capacity than the other gases [12].

By lowering the injection rate, condensate recoveries for all the gases are similar to each other.

Table 2. Reservoir fluid composition

Component	Mole%
N_2	3.15
CO_2	2.15
H_2S	0.08
CH_4	83.32
C_2H_6	5.37
C_3H_8	1.89
iC_4H_{10}	0.43
nC_4H_{10}	0.69
iC_5H_{12}	0.31
nC_5H_{12}	0.26
Pseudo C_6	0.44
C_{7+}	1.03
Fluid Molar Mass (g/mol)	21.85
C_{7+} Molar Mass (g/mol)	141.02
C_{7+} Density (g/cm3)	0.7888

It can be seen in Fig. 7 that during the injection period the capability of CO_2 in removing the condensate in the reservoir is less than the other gases, but after the injection, condensate saturation increases rapidly in all the cases except for the CO_2 injection.

Another difference between CO_2 injection and other gases is in condensate accumulation in the near wellbore region after the injection period finishes. By CO_2 injection the condensate accumulation in this region does not occur, contrary to the other cases in which condensate accumulation in the near wellbore region is even higher than that of natural depletion of the reservoir. Capability of CO_2 in removing the condensate plug from the near gas-condensate wells region and its long-term effect has also been shown in previous studies [12].

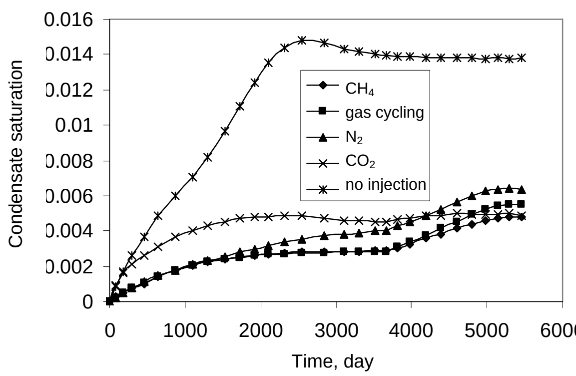

Figure 7. Effect of different injection gases on condensate saturation reduction during the production period (with the injection rate of 1.8 MMSCF/D at the initial reservoir pressure)

3.2- Effect of injection at different reservoir pressures

Injection can be started at the initial pressure of the reservoir (at the time of production), or after the reservoir pressure drops to a certain pressure. The second alternative demands a lower injection pressure so the required facilities will be less expensive.

Our model has been run at the reservoir pressures of 5248 psia (initial reservoir pressure), 4500 psia, 3500 psia and 2500 psia. The effect of injecting at different pressures has been investigated for four different rates. The results for the rate of 75% of the production rate, which are shown in Fig. 8, are discussed below.

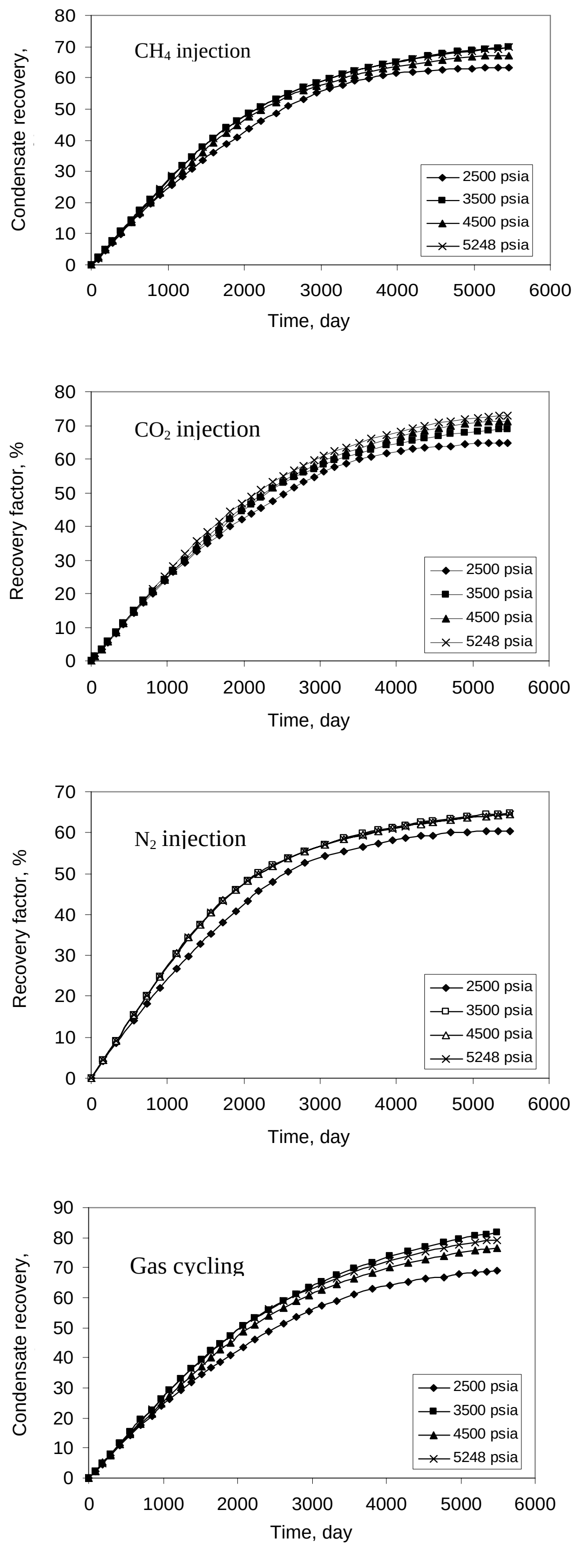

Figure 8. Effect of different injection pressures on condensate recovery with the injection rate of 1.8 MMSCF/D

The results of CH_4 injection and gas cycling with the rate of the 1.8 MMSCF/D (75% of the production rate), show that when injection pressure is 4500 psi, recovery of the condensate reduces, but by further pressure reduction to 3500 psi, the recovery increases to a value equal to the injection at initial pressure or more (in the case of gas cycling).

The graph for N_2 injection shows that recovery does not change much by injecting at the lower pressures than the initial pressure. Finally, condensate recovery by CO_2 injection decreases by decreasing the injection pressure.

3.3- Effect of injection rate

Effect of four different rates (equal to 1, 0.75, 0.5, 0.25 times of the production rate) on the condensate recovery by all the injection gases can be observed in Fig. 9. Injection has been implemented in the initial reservoir pressure.

For the case of CO_2 injection, recovery of condensate for the two highest rates is almost the same, while the recovery of gas (given in Table 2) for the second rate is much higher than the first one. Condensate recovery by N_2 injection is not as sensitive to the rate and is equal for the first three levels of the rate. While the condensate recovery changes only about 5% from the higher rate to the lower one for N_2 injection, this change for CO_2 injection is 14%.

In the case of CH_4 injection and gas cycling, changing the rate makes a noticable change in recovery, especially in gas cycling.

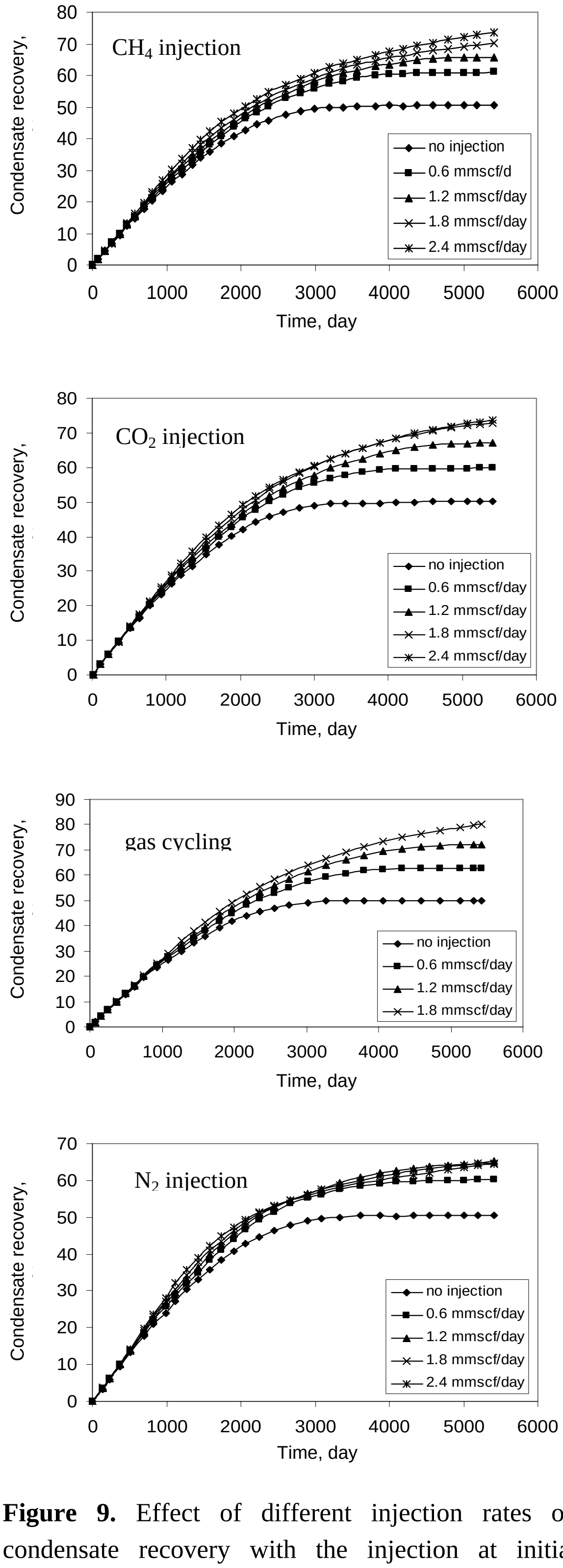

Figure 9. Effect of different injection rates on condensate recovery with the injection at initial reservoir pressure

3.4- Effect of injection duration

Effect of injection duration has been investigated by changing the injection duration from 10 years to 8 and 5 years for all the injection gases with an injection rate of 75% of the production rate, and the results are shown in Fig. 10.

In the cases of CO_2 and CH_4 injection and gas cycling, the recovery increases by increasing the injection duration from 5 to 8 years, while this increase is not considerable from 8 years of injection to 10 years.

In the case of N_2 injection, increasing the injection period from 5 years to 8 and 10 years makes no change in condensate recovery.

3.5- Consideration of gas and condensate recovery factor

The condensate and gas recovery factors of all of the runs of the simulated model have been given in Tables 4-7. In these tables, the effect of all parameters investigated in this study can be observed. The early breakthrough of all injection gases with high injection rates results in considerable reduction in the ultimate gas recovery, and discourages their use in condensate recovery enhancement.

It should be remembered that the result of an injection work in a reservoir greatly depends on the reservoir fluid. The effect of mixing the injection gases with the reservoir fluid can cause different responses in different reservoirs. This results from a thermodynamic analysis of gas injection in two gas-condensate reservoirs [13].

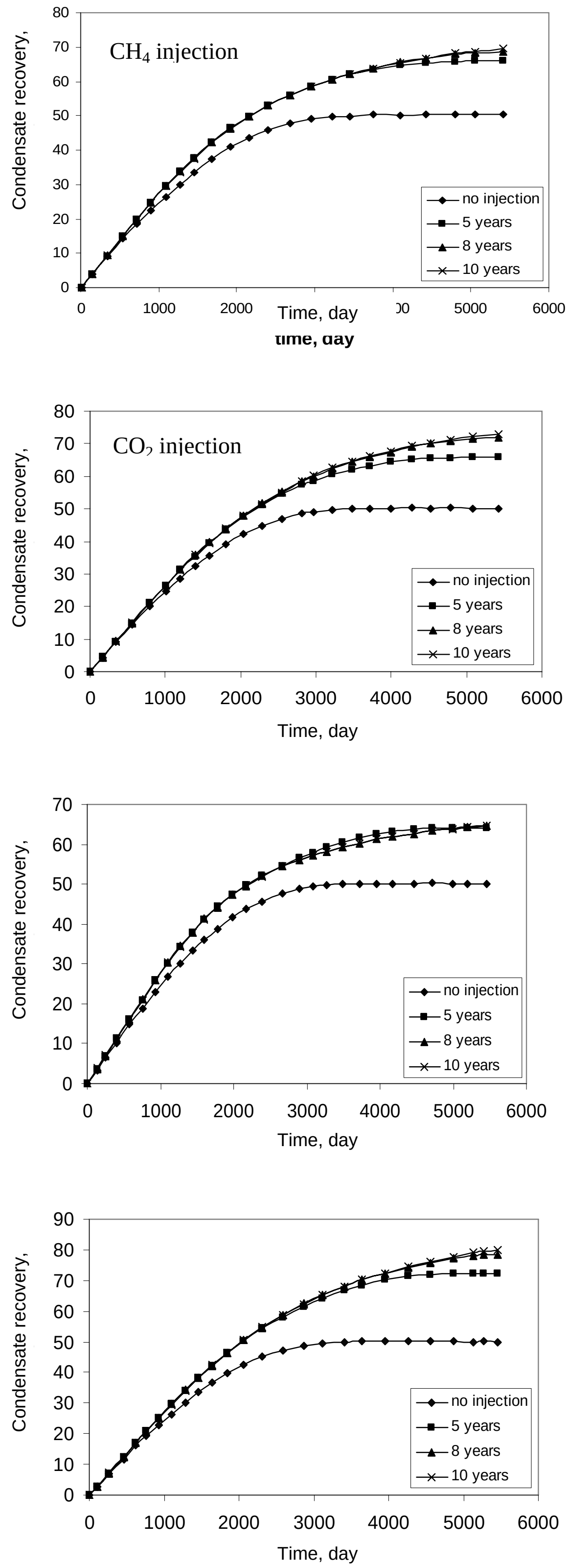

Figure 10. Effect of changing the injection duration on condensate recovery with an injection rate of 1.8 (MMSCF/D)

Table 3. Composition of recycled gas

H_2S	0.0814
CO_2	2.1819
N_2	3.2028
C_1	84.5192
C_2	5.4475
C_3	1.9126
IC_4-NC_4	1.1253
IC_5-NC_5	0.5585
FC_6-C_9	0.9156
C_{10}-C_{13}	0.0554
C_{14+}	0.0000

Table 4. Recovery factors at the injection pressure of 5248 (psia), (initial reservoir pressure)

Rate	**Component** / **Recovery Factor (%)**	**CO_2**	**N_2**	**CH_4**	**Cycling**
2.4 (MMSCF/D)	Condensate	73.828	64.597	73.39	
	Gas	52.376	52.376	52.376	
1.8 (MMCSF/D)	Condensate	72.828	64.938	69.836	80.139
	Gas	78.349	78.524	78.571	78.571
1.2 (MMSCF/D)	Condensate	67.298	64.025	65.589	71.947
	Gas	86.793	88.129	88.49	88.163
0.6 (MMSCF/D)	Condensate	59.989	59.796	60.604	63.003
	Gas	89.009	89.856	89.855	89.646

Table 5. Recovery factors at the injection pressure of 4500 (psia)

Rate	**Component** / **Recovery Factor (%)**	**CO_2**	**N_2**	**CH_4**	**Cycling**
2.4 (MMSCF/D)	Condensate	74.018	64.097	70.489	
	Gas	41.907	41.906	52.404	
1.8 (MMCSF/D)	Condensate	71.197	64.739	67.323	76.365
	Gas	77.839	70.719	78.593	78.593
1.2 (MMSCF/D)	Condensate	65.922	62.978	64.431	70.055
	Gas	86.752	88.218	88.514	88.179
0.6 (MMSCF/D)	Condensate	59.547	58.767	59.921	61.702
	Gas	88.832	89.793	89.855	89.596

Table 6. Recovery factors at the injection pressure of 3500 (psi)

Rate	Component / Recovery Factor (%)	CO_2	N_2	CH_4	Cycling
2.4 (MMSCF/D)	Condensate	72.057	63.617	72.808	
	Gas	52.376	27.077	27.077	
1.8 (MMCSF/D)	Condensate	68.609	64.535	69.927	81.57
	Gas	77.829	59.597	59.597	59.597
1.2 (MMSCF/D)	Condensate	64.247	61.587	63.227	67.668
	Gas	86.628	88.422	88.571	88.211
0.6 (MMSCF/D)	Condensate	58.996	57.231	58.92	59.894
	Gas	88.339	89.428	89.65	89.321

Table 7. Recovery factors at the injection pressure of 2500 (psi)

Rate	Component / Recovery Factor (%)	CO_2	N_2	CH_4	Cycling
2.4 (MMSCF/D)	Condensate	67.33	61.678	64.641	
	Gas	52.405	52.405	52.405	
1.8 (MMCSF/D)	Condensate	64.657	60.689	63.27	69.061
	Gas	77.838	78.592	78.593	78.593
1.2 (MMSCF/D)	Condensate	62.122	58.811	61.202	63.702
	Gas	83.553	85.811	86.894	86.125
0.6 (MMSCF/D)	Condensate	56.988	54.794	66.801	56.747
	Gas	85.92	87.613	88.193	87.63

By doing an economical evaluation the optimum case for the injection can be determined. The factors that can affect the decision of selecting one of the cases studied are: the price of the gas and condensate, the price of the injection gas, expenses of the facilities needed in each injection condition and the separation of the injection gas from the reservoir gas.

4- Conclusions

- Gas cycling is the most effective way to increase the condensate recovery.
- By reducing the injection rate capability of CO_2, CH_4, N_2 and gas cycling in condensate recovery approaches together.
- CO_2 injection results in removing the condensate accumulated in the near wellbore region during the injection period and it can also prevent the accumulation of the condensate for a certain time after the injection is stopped.
- Condensate recovery by N_2 injection changes very slightly when the injection is implemented in different reservoir pressures.
- Injecting at pressures lower than the initial pressure of the reservoir results in greater or the same condensate recovery in some cases (compared to the case of injecting at initial reservoir pressure).
- Condensate recovery by N_2 injection changes slightly by changing the injection rate.
- Increasing the injection duration from 5 years to 8 and 10 years has no effect on the condensate recovery when N_2 is injected. In cases of CO_2 and CH_4 injection and gas cycling the recovery increases by increasing the injection duration, but this increase is not considerable from 8 years of injection to 10 years.

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