Gravity Drainage Process For Miscible and Immiscible Co2 Injection Process

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Abstract. In this paper, CO2 injection for enhancing oil recovery assisted by gravity drainage using reservoir simulation (using CMG's IMEX and GEM simulators) for a miscible and immiscible process is studied. The reservoir pressure declines with time and reaches a point where the fluids from the reservoir will not flow into the wellbore. Then the reservoir is assisted by additional pressure support under secondary recovery methods by gas injection or water flooding. For the conditions where the reservoir is having immobile oil due to relation of fluid and rock properties enhanced oil recovery techniques are adopted. CO2 is used under gas injection techniques is one of the most efficient and economic method to recover the oil. The gravity drainage process of CO2 when injected into the reservoir is observed in this paper. To understand and analyze the process of gravity drainage under miscible and immiscible CO2 injection a 50°API gravity oil was selected to study under simulation model of selected grid size. The analysis was made for seven different cases and their relations with time, production of water and GOR are represented.

Keywords: CO_2 injection, gravity drainage, gas injection, miscible and immiscible flow, API gravity, reservoir simulation.

1 Introduction

Enhanced oil recovery is to recover the immobile oil when the reservoir pressure declines and flow of oil ceases. There are various EOR techniques used to recover the left-over oil. Gas injection technique is the most efficient economic method of enhancing the recovery rates. The gas injection is carried out as a miscible displacement or immiscible displacement based on the reservoir. The miscibility of an injected gas directly depends on the MMP(Minimum Miscibility Pressure). The CO_2 injection being the one of most efficient enhanced oil recoveries, the field studies indicate that there are no investigations on the gravity drainage process for immiscible & miscible CO_2 injection. There is also a lack of research on the gravity drainage process for 50 °API gravity oils. An attempt was made to study the CO_2 – assisted gravity drainage to understand the mode of miscibility development, gas injection, molecular diffusion and heterogeneity through grid refinement studies. Thus, a study is carried out by using Computer Modeling Group (CMG), IMEX and GEM simulator by selecting compositional models based on equation of state and pseudo-miscible. To avoid premature breakthroughs and viscous fingering through oil zones the injection rates are maintained below the critical levels.

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To study CO_2 – assisted gravity drainage enhanced oil recovery method's, miscibility development and recovery performance on 50 °API gravity oils compositional models a set of seven combinations of CO_2 injection rates and production rates of oil. This process considers maintaining the process at void balance conditions. In this study, the data is considered from optimized oil recovery of vertical injection of CO_2 and horizontal oil production from a regular well. A period of 132 years set for reservoir simulation for miscible and immiscible CO_2 injection.

Table 1. Rate Constraints of The Wells

CASE	Rate Constraints/ Well		
	iCO_2 MMSCFD		Q_o, BPD
	Immiscible	Miscible	
I	1.50E+06	2.09E+06	4000
II	3.32E+06	4.70E+06	9000
III	5.62E+06	7.80E+06	15000
IV	1.00E+07	1.40E+07	20000
V	2.00E+07	2.74E+07	52500
VI	3.00E+07	4.10E+07	80000
VII	4.00E+07	5.60E+07	108000

2 Comparing

- **INCREMENTAL OIL RECOVERY**

The production of oil that was left for secondary recovery is incremental oil recovery.

$$\text{Incremental EOR} = \frac{\text{Incremental Oil Recovered in } CO_2 - \text{Assisted Gravity Drainage}}{\text{Oil-In-Place at the start of } CO_2 \text{ injection}}$$

The immiscible and miscible rate constraints of the incremental oil recovery performance of CO_2 injected with respective pore volumes are represented by figures 1 & 2.

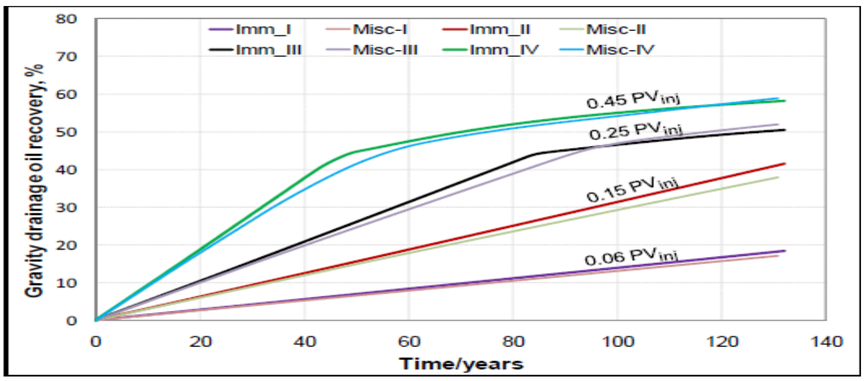


Fig. 1: Comparison between incremental miscible and immiscible gravity drainage assisted by CO_2 oil recovery in rate-constraints from Case-I to Case-IV

From the figure 1 graph, it is clear that the recovery rates are less for miscible compared to immiscible for a case I & II low rate constraints. But for cases III & IV there is a marginal cross for miscible over immiscible recovery. For Case – V the incremental recovery showed relatively higher for miscible compared to the immiscible process. The same was seen for Case-IV but there was an early flood front 30 years before.

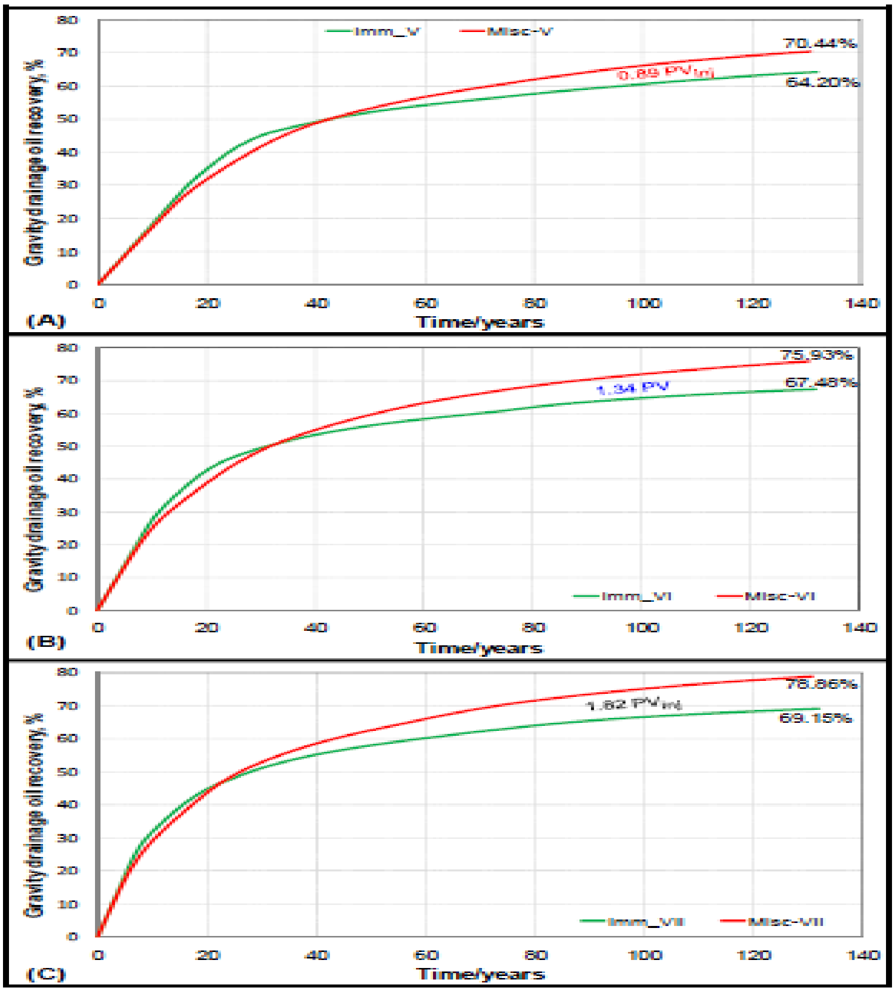


Fig. 2: Comparison - Incremental CO_2-assisted gravity drainage oil recoveries in both the immiscible and miscible process from Case-V to Case-VII

For Case – VII there was the highest incremental recovery from the higher CO_2 injection rates that accounted a 79%. This is 10% more than the immiscible flood for the same conditions in Case-VI.

From a detailed understanding of the above curves, it is clear that the immiscible recovery projected higher levels than miscible till the CO_2 flood front is achieved.

- **GOR:**

The GOR (Gas Oil Ratio) of Case IV – Case VII for the taken rate constraints showed a thinning curve for the miscible process and thick curves for the immiscible process. For Case-VII immiscible process had a maximum of 96000 GOR and 85875 for the miscible process. GOR in miscible tends to stay low due to the injected high-pressure gas compress the condensate gas. But as the selected oil is of 50 °API gravity which is a light oil that may produce condensate gas. This will show gas production after a breakthrough.

- **WATER PRODUCTION:**

For Case IV-VII the water production from the water breakthrough by the aquifer below the oil zone for miscible and immiscible is zero or negligible. This is as the horizontal reservoirs are perorated and produced at parallels. The vertical injection of CO_2, the proper selection of producing zone and correct selection of control or completely nullify the chances of water coning.

- **RESERVOIR PRESSURE:**

As the reservoir pressure declines with time as production happens, the study of the average pressure decline for the life of the reservoir is critical and highly needed. From the set of data combinations, there was a decrease of 60 psia till the drainage area achieved CO_2 flood front in the horizontal production well which is a 2.2 psi/year decline by 2022. The drop in oil production and the rise in GOR indicate the CO_2 flood front arrival. The average pressure for Case -IV, VI & VII after production for 132 years under immiscible process is observed a decline of 22,70 and 100 psi respectively. The wells with high-rate constraints have more pressure drops than low rate well constraints. For the three cases of IV, VI & VII the pressure drops are as 0.17 psi, 0.54 psi, and 0.77 psi per year correspondingly which explains that the wells with low-rate constraints have less pressure drop.

3 Study Of Mechanism

- **IMMISCIBLE**

For immiscible CO2 gas injection assisted by gravity drainage EOR method block (21,20,7) is selected to evaluate the contributing mechanisms are demonstrated by figure 3 are changes that are associated with properties over 132 years of production which is done by understanding the oil saturation profile by combining with pressure in reservoir and GOR. The oil saturation in case-V and VII for 16 and 7 years respectively in a block (21,20,7) remains constant at 0.82.

- **MISCIBLE**

From earlier comparative studies it is shown that the incremental recovery of the miscible flood was high than the immiscible process. The responsible mechanisms that aided high recovery are illustrated by understanding oil saturation, gas saturation, and oil viscosity properties.

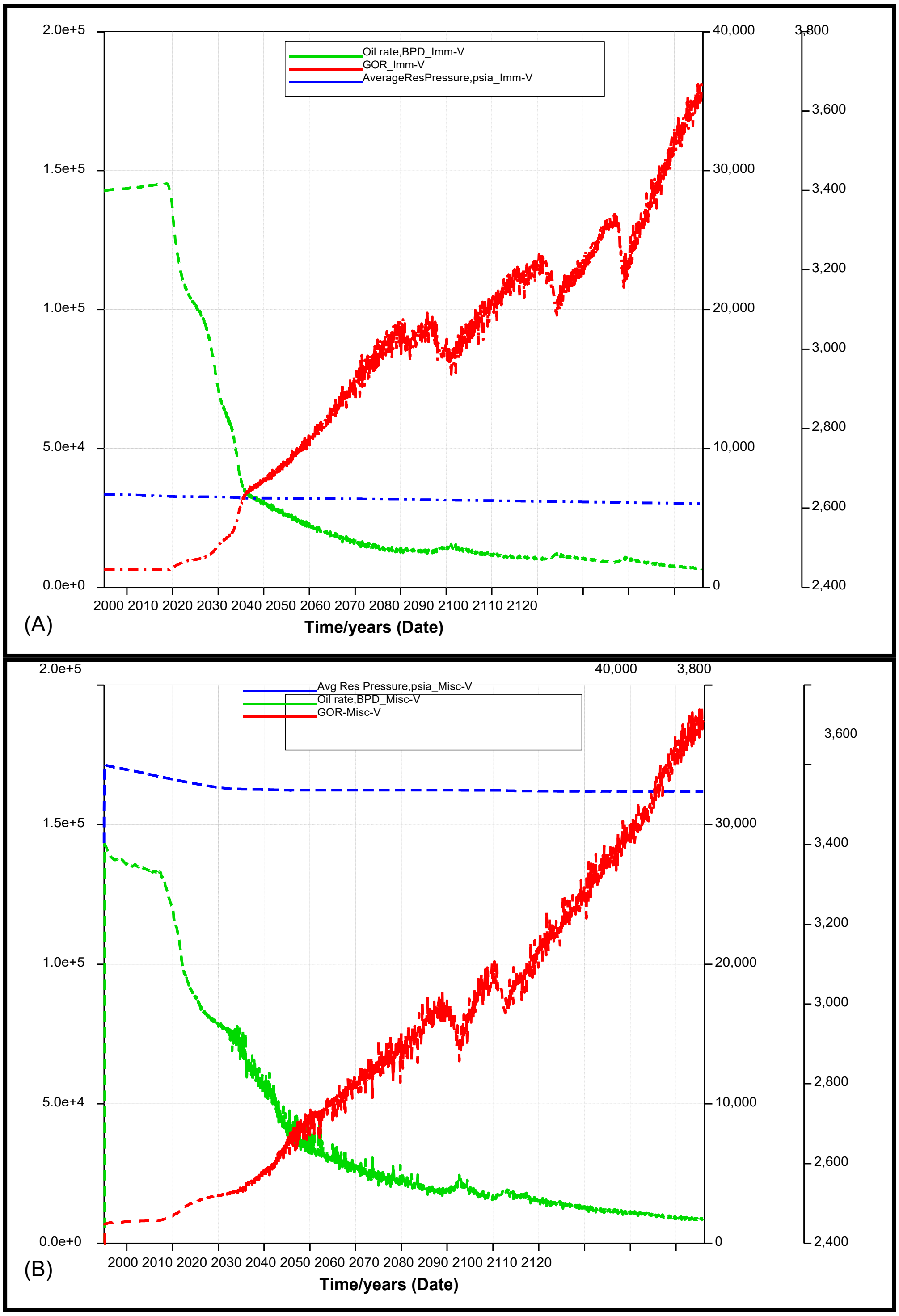
To sum up, the average reservoir pressure is the dominating mechanism that contributed to oil recovery by EOR process of gravity drainage assisted by CO_2 under miscible and immiscible process. This is well understood by collaborating oil rate Barrel Per Day (BPD), GOR (ratio of gas oil) and average pressure in reservoir for the miscible and immiscible process are discussed in detail.

3.1 OVERALL MECHANISMS: IMMISCIBLE AND MISCIBLE PROCESS

In EOR process for both the miscible and immiscible gravity drainage assisted by CO_2, the average pressure in reservoir is the parameter which itself explains the involved mechanism of oil recovery. Figure 3 shows the oil rate per barrel per day, GOR (ratio of gas oil) and the average pressure in reservoir in both miscible and immiscible process in Case-V were plotted in order to understand.

At initial stage of immiscible flood of CO_2 the average pressure in reservoir is 2633 psia in March 1995 but at end (April 2126), it is nearly 2598 psia (see in Figure 3A**)**. This was dropped by only 35 psia, with 026 psia rate of average every year in 132 years of simultaneous production and immiscible CO_2 injection. The production of oil begins just after the injection of CO_2 (see in figure 3A**).** In the secondary flood of CO_2 it was observed that the single phase oil flow and the water phase was immobile. The difference in the higher density between gas and oil at the time of secondary immiscible flood and that promotes the under gravity oil drainage behind the flood front of $CO_{2.}$ This type of drained oil joins with oil bank formed earlier the flood front of CO_2 for further contribution of oil-displacement which takes place before the flood front of CO_2.

The majority of oil was in oil bearing zone in oil bank. In respect with the sharp drop in saturation of gas the saturation of oil in block (25, 14, 6) is slowly increased in 8 years of miscible process from the start of miscible in 1995 was shown in figure 3. Once the arrival of gas front to upper block, then that was an immediate proximity to the gas cap, and the saturation of oil retains its normal value of 0.80 (see in Figure 2A) and which will remain/stands there for total 65 years (until 2070). Corresponding saturation of oil slowly falls to the value of 0.10 and it continues to fall gradually while producing very slow recovery of oil (see in Figure 2C). Even though with 65 years of S_g constant profile, the viscosity of oil continues to increase. It indicates that medium components and heavy components were extracted from block in oil reservoir, which leads to increase in viscosity and reduction in oil-volume. The block (25, 14, 6) which witness a complete recovery of oil is indicated by zero values of oil viscosity in year 2087 (see in Figure 2B). The maximum saturation values of oil shown in Figure 2A and respective zero saturation oil shown in figure 2C and this is done by the gravity drained oil's trailing edge.


Oil rate,BPD_Imm-V
GOR_Imm-V
AverageResPressure,psia_Imm-V
2.0e+5
1.5e+5
1.0e+5
5.0e+4
0.0e+0
40,000
30,000
20,000
10,000
0
3,800
3,600
3,400
3,200
3,000
2,800
2,600
2,400
2000 2010 2020 2030 2040 2050 2060 2070 2080 2090 2100 2110 2120
(A)
Time/years (Date)
Avg Res Pressure,psia_Misc-V
Oil rate,BPD_Misc-V
GOR-Misc-V
2.0e+5
1.5e+5
1.0e+5
5.0e+4
0.0e+0
40,000
30,000
20,000
10,000
0
3,800
3,600
3,400
3,200
3,000
2,800
2,600
2,400
2000 2010 2020 2030 2040 2050 2060 2070 2080 2090 2100 2110 2120
(B)
Time/years (Date)

In the year of 2013, it was observed that sudden fall of oil saturation and sharp increase in gas saturation in the block (25, 14, 7). It is pointed by the gas flood front arrival. During this time oil reservoir can experience both minor extraction and oil swelling represented by corresponding rise and fall of oil viscosity in figure 2B**.** But after the arrival of gas flood front, viscosity of oil experiences only its rise, indicating that the the mechanism which is used to recover the reservoir oil which was left behind the flood front of CO_2 takes important role. At this time the values of oil saturation remains stable at values about 0.04 (figure 2C). Once oil in reservoir is gravity drained downward from upper blocks (25, 14, 6), saturation of oil starts to fall gradually earlier than its complete recovery in the year of 2120 (nearly over 32 years after gas flood front arrival). Abrupt vertical drop in the values of viscosity indicated by trailing edge in leaving (25, 14, 7) block of oil which is gravity drained.

Same oil viscosity, oil saturation and gas saturation profiles are shown in block (25, 14, 8). The arrival of flood front in gas is indicated by the reduction in oil saturation and rise in gas saturation. The viscosity of oil will experienced its decline which is coming from swelling earlier than arrival of CO_2 flood front but rise in its consistent later. These results again indicate that the oil in reservoir behind leading edge of gas flood front was recovered by the mechanism used to extract, along with gravity drainage mechanism.

For further confirmations, the observations are recorded by the sectional-views of oil saturation, gas saturation and oil viscosity properties in these following blocks and are represented symbol of 'star' in Figure 4A via figure 4L for variations occurred in following properties from begin (1996) to the last part (2126) of the Case-VII in secondary flooding in miscible of CO_2. The layers of oil zone is indicated by the red numbers on the top left of right in figure, and top down in production is target zone and it also indicates the horizontal and vertical production (layer-8) wells. The starting properties of this block (25, 14, 6) at initial stage of miscible flood that is in the year of 1995 are shown by symbol star in figure 4A, 4B, and 4C. The majority of oil recovery **(**figure 4F) effected the gas saturation that is increased by a value which is higher than 0.80 was shown in Figure 4D and this is by using B-L type displacement. Though the oil components are extracted from this block (figure 4E**)** is indicated by corresponding rise in viscosity of oil in layer-6.

After reaching the block (25,14,8) the gas flood front in the year of 2024 that was shown in figure 4G and then it is followed by the front of miscible. Due to the continued gas production, the viscosity of oil in the year looks like rise in some blocks and in some upper blocks in layers 7 and 6 seems reduced, nearly zero values (figure 4H**)**. The zero values indicates that the oil was completely recovered that was behind the flood front of gas by extracting the components of oil. It has to be remember the oil was not completely recovered from these layers. figure 4J shows that the increase in gas saturation not attain the values in 2126 that are observed in the year 2024, it was when first breakthrough of gas occurred. As shown in figure 6-8K, The values of viscosity of oil drops to zero in almost of the layers 6 and 7. It's values reached higher in 2126 than (in layer-8) those observed before in 2003, 24. This explains the further extraction process at the time of downward movement in the zone miscible along continuing to drain the oil present under gravity which was from upper layer. figure 6-8L shows the respective saturation of oil at final stage of miscible flood of CO_2.

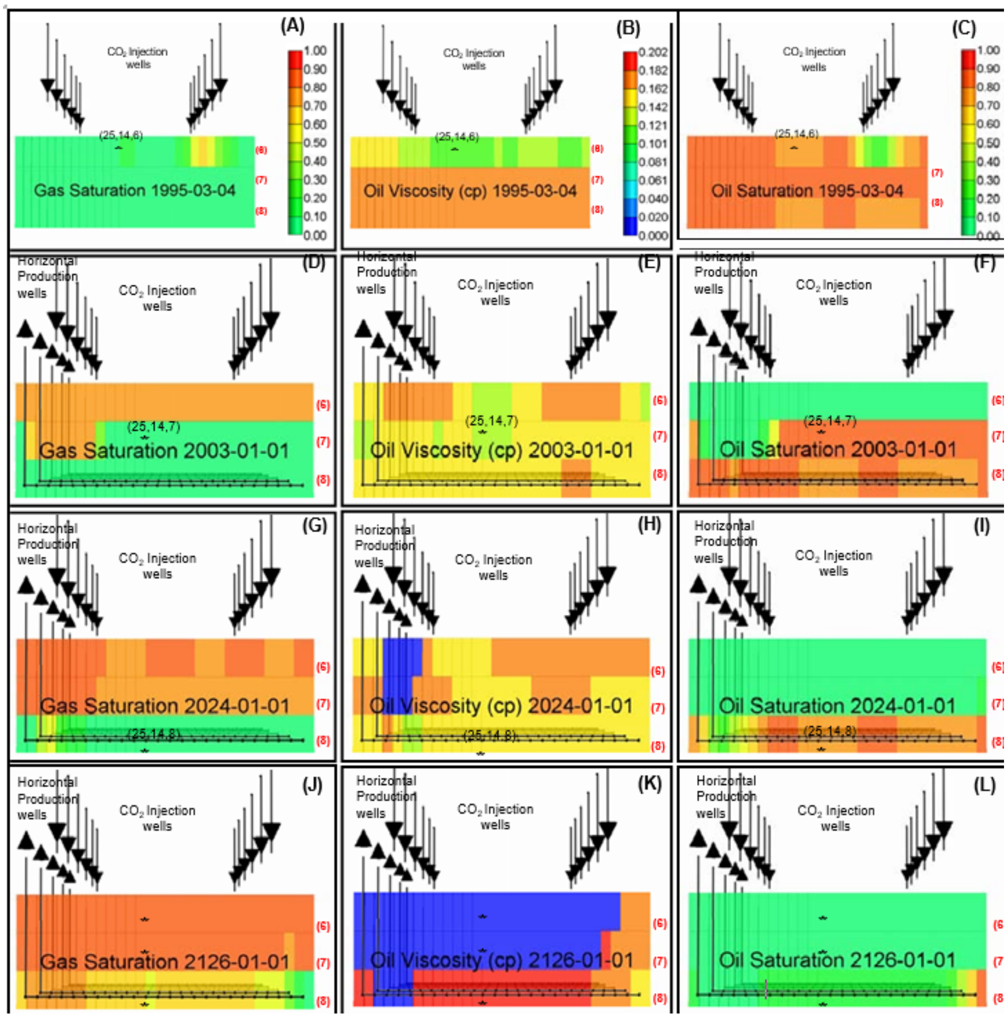


Fig. 3. Mechanisms for Oil recovery except the mechanism of gravity drainage in blocks (25, 14, 6), (25, 14, 7) and (25, 14, 8) in top-down EOR process of gravity drainage assisted by CO_2. Process Selection Map: Miscible vs. immiscible EOR process of gravity drainage assisted by CO_2.

To obtain optimized oil recovery from miscible or immiscible CO_2 injection, the ultimate incremental oil recoveries of selected well rate constraints of Case I – VII vs incremental pore volumes of CO_2 injected is shown in figure 4.

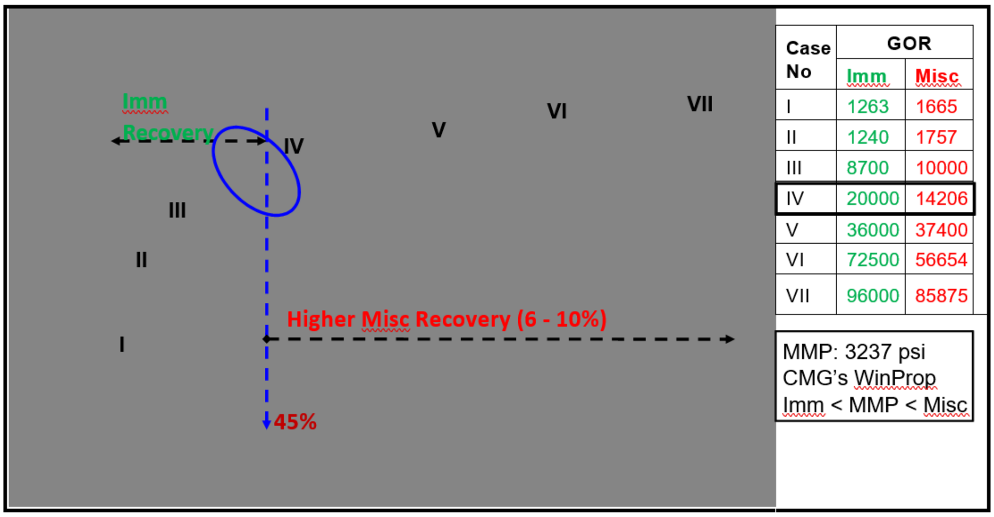


Fig. 4. General selection map for immiscible Vs. miscible process - Case-I via Case-VII

From the plot of ultimate recovery vs pore volume, CO_2 injected (PV_{CO2}) for Cases I, II & III, the immiscible recovery is high over miscible. For Case IV of the pore volume of 0.45 CO_2 injected (PV_{CO2}) achieved identical oil recovery with immiscible at 58.25% and miscible at 58.88% of CO_2 -assisted gravity drainage EOR processes. This scenario reversed for Cases V, VI & VII well constraints. They have shown 70.44, 75.93 and 78.86% for Case-V, Case-VI and Case-VII respectively with ultimate recoveries of 64.20%, 67.48% and 64.20%.

GRID REFINEMENT: For reservoir with 50 ºAPI Oil

As there are no investigations on the recovery of gravity drainage oil assisted by CO_2 a base model (50 × 30 × 10: 600 × 400 × 150) considered for the above studies to conclude the miscible and immiscible CO_2 injection above 132 years can yield optimum recovery of oil of 78.85% and 69.15% respectively in process of EOR gravity drainage assisted by CO_2. The effects of the grid – size and grid – thickness for miscible CO_2 injection are tabulated below considering the base model of the grid (50 x 30 x 10) for Case – VII & Case – IV with each grid size of (600ft x 400ft x 150ft).

EFFECT OF GRID SIZE

To understand the effect of grid size on the incremental recovery of oil the base model is reduced to two dimensions (x and y). So that initially the base model (600ft x 400ft) is reduced to half (300ft x 200ft) and one fifth (120ft x 80ft). The incremental recovery of half base model (300ft x 200ft) for Case – VII is 79% which is identical to the two dimensions base model (600ft x 400ft). The same incremental recovery for Case IV was achieved at 45% of CO_2 injected PV (Pore Volume).

Table 2. Details of grid thickness (layers) and grid size studies for both the Case-VII and Case-IV

	Case	Number of grid blocks (i, j, k)	Grid dimensions (x, y, and z)	Comments	Comparison parameters
Grid size	I	50 × 30 × 10	600 ft × 400 ft × 150 ft	Base Model	Incremental EOR, GOR and water cut vs. PVCO2inj; and years of production
		50 × 30 × 10	300 ft × 200 ft × 150 ft	x & y dimensions Reduced	
	II	50 × 30 × 30	600 ft × 400 ft × 50 ft	Base Model	
		50 × 30 × 30	120 ft × 80 ft × 50 ft	x and y dimensions reduced	
Grid Thickness	I	50 × 30 × 10	600 ft × 400 ft × 150 ft	Base Model	
		50 × 30 × 30	600 ft × 400 ft × 50 ft	Layer thickness Reduced	

4 Conclusion

It is an attempt in order to optimize recovery of oil by using EOR process in gravity drainage assisted by CO2. The aim of these all investigations is (1) To identify best mechanism and to develop one general method selection map in order to choose in between the miscible and immiscible recovery process; (2) For study grid size effects using grid-refinement. Lastly, operational mechanisms which are used to recovery of oil in gravity drainage of all gravity methods which are assisted by CO_2 are identified.

In every study on reservoir simulation, to satisfy/agree the injection rates of CO_2 are kept smaller than the stable and critical rates of gas injection.

The selection of miscible and immiscible EOR process of gravity drainage assisted by CO_2 is guided by the map which is generated by the use of numerical simulations in base model (50 × 30 × 10: 600 ft × 400 ft × 150 ft) (figure 4). Furthermore, it was suggested that base model produces the optimum recovery of oil is 78.85% and 69.15% in miscible and immiscible process respectively about 132 years of injected CO_2.

The dimensions of x and y are reduced nearly half (300 ft × 200 ft) of the original base model dimensions (600 ft × 400 ft) in case of both IV, VII in well rated constraints combination while studying the grid size effect in the incremental recovery. Figure 1 concludes that at 180 pore volumes of injected CO_2 produces similar incremental recovery of oil of 79% by the reduced grid size (300 ft × 200 ft × 150 ft) and original base model (600 ft × 400 ft × 150 ft). At injected 45% PV_{CO2} in case-IV of same profile of oil recovery (60%) was attained. From these results it is clear that in good rated constraint combination indicates the effect of grid size has negligible in incremental recovery at reservoir scale using EOR process of gravity drainage assisted by CO_2. Identical outcomes are presented by Gillham and Fassihi (1993) in the studies of air injection but they varied just the length of x-dimension.

The thickness of grid is minimized to 50 ft when compared with the base model has thickness of 150ft. The performance of the gravity drainage incremental recovery of oil assisted by CO_2 which points out reduced model produces 6-16% (Case-VII), (case-IV) of incremental recovery of oil when compared to base model. By these results it is clear that with smaller grid models yields a better incremental profile of EOR even at lower volumes of pore with injected CO_2. It provides the effective oil drainage which has gravity-drained from upper to beneath layers. Furthermore, the oil present in these blocks is not allowed. This really matters in layer in which horizontal production well was completed. According to the outcomes of Gillham and Fassihi (1993) and Ypma (1985) concluded that for the optimizing the recovery of oil the layers in the bottom most must be thinner. The investigations in present study suggested that the thin layers can facilitate the optimum recovery of oil in gravity drainage also in upper layers.

The optimized grid recovered 98.4% (50 × 30 × 30: 120 ft × 80 ft × 50 ft) at 9 PV_{CO2inj} (over 132 years) and also 94% at 3 PV_{CO2inj} (over 40 years) recoveries which are incremented in the process of miscible at one-fifth low rate of oil production. Due to this higher recovery leads to utilization of optimized grid for all remaining simulations. Diffusion effects that are present in homogeneous reservoir (k_V/k_h=1.0) are neglected in these studies.

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