Carbon Dioxide Injection to Control Water Encroachment in Water-Drive Gas Condensate Reservoirs

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Abstract

The recovery of gas reservoirs are usually high because of high mobility and low residual gas saturation. Although the gas reservoirs with companion of active aquifer has low recovery. Encroachment of water in these reservoirs traps a considerable volume of gas and increases the maximum residual gas saturation which results in reduction of gas and condensate production. Generally, recoveries of water-drive gas reservoirs vary between 35-75 percent whereas depletion-drive reservoirs exhibit recoveries near to 90 percent. There are some methods to increase the recovery of these reservoirs i.e. blow-down and up-dip production. Even though this methods have many disadvantages include economic and operation problems. In this work a new method was proposed to reduce the water encroachment and sweep the reservoir gas effectively and enhance the hydrocarbon recovery consequently. For this aim a condensate gas reservoir model with two vertical wells was simulated. The injection was performed above the bottom-up aquifer from a horizontal well. Three case of inactive aquifer (Case I), active aquifer (Case II) and active aquifer with CO_2 injection (Case III) was studied consequently. Finally, the effect of CO_2 dissolution and reservoir heterogeneity in term of Lorenz coefficient were studied in this reservoir. This study shows that injection of CO_2 can sweep the reservoir gas before water invades the pores. So, this process increases the recovery of gas about 1.8 times and condensate about 3.40 times). Moreover injection of huge volume of CO_2 (about 29.3 million tonne) without significant CO_2 production can be interesting as environmental point of view and can be considered as CO_2 storage process. The dissolution of CO_2 decreases the sweep efficiency and reduces the condensate recovery subsequently. However, it has no significant effect on gas production. Although, reservoir heterogeneity decreases the efficiency of process, the recovery of hydrocarbon is still higher in comparison with case of no CO_2 injection.

Keywords

Water-drive, Gas condensate reservoir, Carbon dioxide, Storage, Recovery

1. Introduction

One of the important parts in reservoir development and management is prediction of production. The recovery efficiency of gas reservoirs with no companion of aquifers are usually high (Lee & Wattenbarger, 1996). Generally, recoveries of water-drive gas reservoirs vary between 35-75 percent whereas depletion-drive reservoir exhibit recoveries near to 90 percent (Mckay, 1974). Initially, physical properties such as the residual gas saturation (S_{gr}) behind the water front govern ultimate recovery of water-drive gas reservoirs (Bassiouniz, 1990). With increasing production and pressure drop, water move to pores and throats that filled with gas and the water displace the gas incompletely.

As illustrated before, although recovery range from water drive in gas reservoir is wide and low, in simple gas reservoir (without water drive) is almost fixed near 90 percent, so some technique has been used for increasing recovery in gas reservoir. One of these methods is the blow-down technique (increasing gas rate to produce gas before encroachment) (Chesney, Lewis, & Trice, 1982). Up-dip production technique (producing gas from up-dip and water from down-dip) is another method for increasing gas recovery. Although, these methods have some disadvantages i.e. water coning and economic inefficiency (Batycky et al., 1998).

Encroachment of water in the pores traps high volume of gas as mentioned above. So, depleting the reservoir pore volume before water invasion is a solution in face of water-drive gas reservoirs. In this work the process of carbon dioxide (CO_2) injection with aim of sweeping reservoir base gas and reduction of water movement to reservoir were studied. This process can deplete the base gas of the pores before water entrap them. Also, injection of CO_2 in this reservoir cause carbon sequestration which is interested for environmental issues these days.

Measurement of the atmospheric CO_2 concentrations for the last 250 years illustrates its increase from 270 to more than 370 ppm. Experts project that carbon dioxide emissions account for about two third of the potential global warming (Cakici, 2003). Burning fossil fuels (oil, gas and coal) for energy production emits 27 billion tons of CO_2 in the atmosphere annually (Gupta, 2010). One of the effective solution for decreasing the emission of CO_2 is direct capturing and storing in deep geological formations, which is known as carbon capture and storage (CCS) (Faiz, Saghafi, Barclay, Sherwood, & Whitford, 2007). Several studies have reported on the numerical simulation and study of the CO_2 storage process, usually in order to establish more efficient schemes to store larger volumes of gas, e.g. Kumar et al. (2005), Leonenko and Keith (2008) (Ghaderi, Keith, Lavoie, & Leonenko, 2011). Ghomian et al. (2007) have studied the coupled CO_2 sequestration and enhanced oil recovery (Ghomian, Pope, & Sepehrnoori, 2007). Zangeneh et al. (2013) co-optimized the process of Enhanced Gas Recovery/Carbon Capture and Storage (EGR/CCS) in a gas reservoir in south Iran using Genetic Algorithm (GA) (Zangeneh, Jamshidi, & Soltanieh, 2013).

2. Model Description

A compositional model was hired for this study to simulate the injection process. The model had 60×60×10 corner point cells. It owns two production and one injection wells. The production wells are vertical and was placed at corner of the cubic model and the injection well is consist of a main vertical well and a horizontal sidetrack which was placed at the diagonal of the cube. Figure 1 depicts a 3D view of the model and its wells.

The reservoir contained condensate gas with 7 components which was modeled using Peng-Robinson Equation of State (EOS). The composition of the reservoir fluid is represented in Table 1. The reservoir rock properties was simulated using Corey model with Corey index of 6 for gas and 4 for water. The Corey index for water/condensate and gas/condensate phase were represented as 3. The reservoir has an active bottom drive aquifer which was modeled using Carter Tracy model and its properties is shown in Table 2. Table 3 shows the static properties of the reservoir.

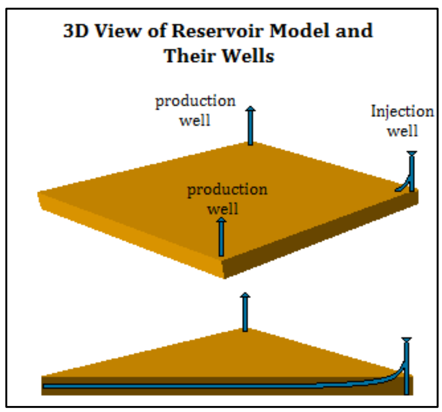

Figure 1. 3D view of reservoir model and their wells

Table 1. The composition of reservoir fluid

Component	Mole fraction (%)	Molecular weight (gmole)
Methane (CH_4)	69.14	16.04
Ethane (C_2H_6)	8.69	30.07
Propane (C_3H_8)	5.91	44.10
Plus fraction (C_{4+})	16.26	96.51

Table 2. The reservoir aquifer properties

Property	Unit	Value
Aquifer permeability	md	200
Aquifer porosity	%	25
Angle of influence	Degree	360
Water salinity	ppm	30000

Table 3. The static properties of the reservoir

Property	Unit	Value
Reservoir length	m	3000
Reservoir width	m	3000
Reservoir height	m	200
Temperature	°C	93
Initial pressure	bar	180
Average porosity	%	15
Average vertical permeability (base case)	md	0.6
Average horizontal permeability (base case)	md	6.0
Water/gas contact depth	m	-2150

3. Production and Injection Scenarios

In this work three cases were studied to investigate the effect of aquifer on cumulative gas and condensate production. In the second case (Case II) the production process by depletion scenario was simulated. This case can show the base case of the production in a water-drive gas condensate reservoir. The production time is 30 years with constant bottomhole pressure of 100 bar. The water-cut limitation of 10 percent controls the water production of the reservoir. In the first case (Case I) the effect of aquifer on reservoir was omitted by deactivating it. Comparison of the Case I and II can illustrate the effect of aquifer activity on gas and condensate production. The production condition of this case is like the last case. Finally, in the last case (Case III) CO_2 injection process was simulated. In this case the injection scenario was began at seventh years of production with rate of 2 MMSCMD (million standard cubic meters per day). The objective of this case was studying the effect of CO_2 injection on reduction of aquifer water encroachment and gas production.

4. Results and Discussions

Production of gas from a water-drive reservoir can trap a significant amount of gas in pore volumes. Injection of CO_2 can sweep the pore volume fluid content before water invade it. Figure 2 depicts the cumulative gas production of three mentioned cases. This figure illustrates that active aquifer (Case II) decreases the cumulative gas production of the reservoir in compare to inactive aquifer (Case I) (cumulative gas production of Case II is about 0.70 times of Case I). This figure also shows that injecting CO_2 in the reservoir increases cumulative gas production (Case III) (cumulative gas production of Case III is about 1.80 times of Case II and 1.22 times of Case I).

Figure 3 compares the cumulative condensate production of three cases. Considering this figure it can be concluded that encroachment of water in the reservoir decreases cumulative condensate production (cumulative condensate production of Case II is about 0.94 times of Case I).

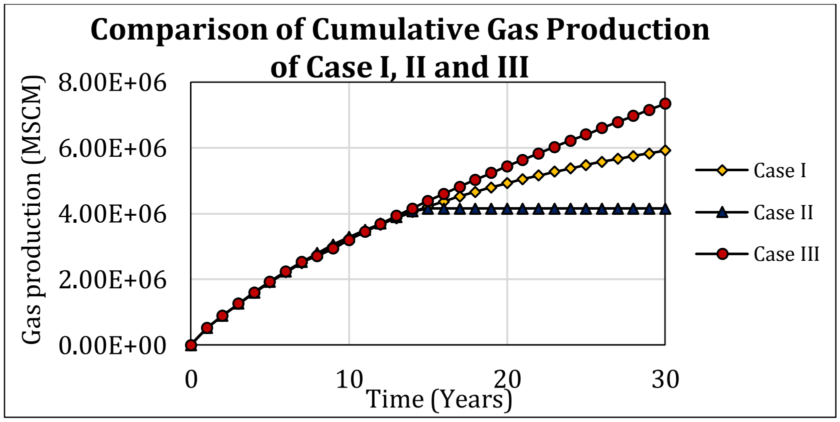

Figure 2. Comparison of cumulative gas production of Case I, II and III

Although the effect of aquifer on gas production is insignificant, CO_2 injection has an enormous effect on condensate production and increase it significantly (cumulative condensate production of Case III is about 3.40 times of Case II and 3.19 times of Case I). Comparing the amount of CO_2 injected and produced shows the effectiveness of this process. The net cumulative CO_2 injection of the process is about 16.3 MMMSCM (29.3 million tonne).

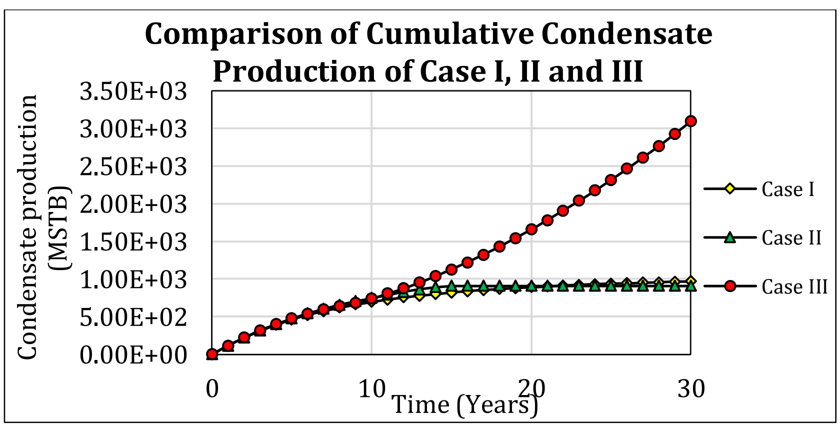

Figure 3. Comparison of cumulative condensate production of Case I, II and III

Figure 4 depicts the amount of cumulative CO_2 production on the surface. As is clear in this figure the amount of CO_2 production of the reservoir is zero till the 25^{th} years. Although it is about 40.3 MSCM (72.5 tonne) at the end of the process. This shows that amount of CO_2 production is negligible and about 0.00025 percent of injected CO_2. Figure 2-4 illustrate that injection of CO_2 in a gas condensate reservoir under water-drive production can increase the amount of gas and condensate recovery. This process can store a large amount of CO_2 with negligible CO_2 production which is an interesting process for environmental aspects. Injection of carbon dioxide sweeps the reservoir base gas before water invades the pore volumes. In fact injection of CO_2 enhances gas recovery and maintains the reservoir pressure which prevents water movement because of low pressure drawdown in the reservoir.

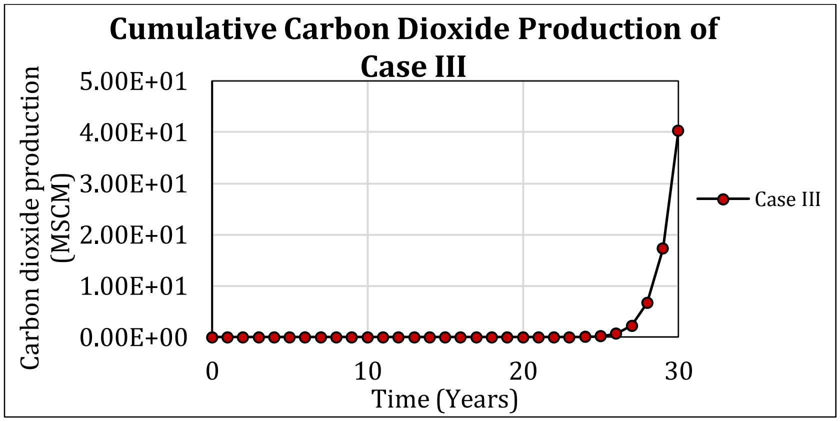

Figure 4. Cumulative CO_2 production of Case III

Figure 5 shows the profile of water and CO_2 saturation of Case III versus depth. This figure demonstrates that CO_2 injection prevents the encroachment of water by filling the pore volumes.

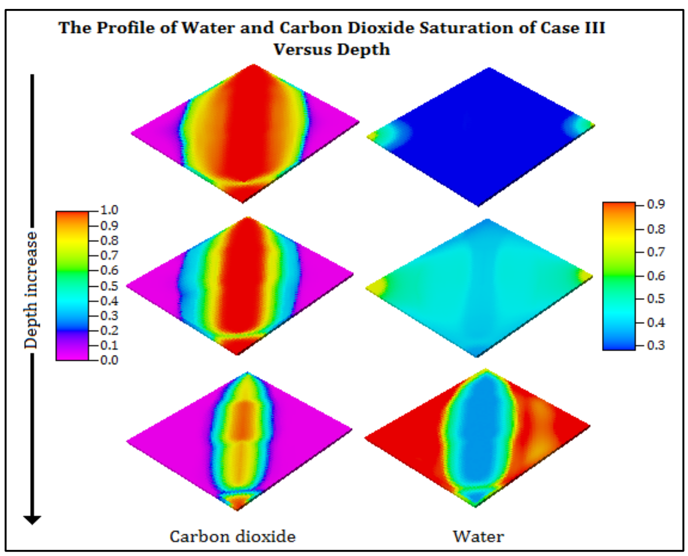

Figure 5. The profile of water and carbon dioxide saturation of Case III versus depth

4.1. Effect of Dissolution of Carbon Dioxide in Reservoir Water

Injection of CO_2 in geological media includes variety of strongly coupled physical and chemical process as multiphase flow, solution-dissolution kinetics, solute transport, hydrodynamic instabilities due to displacement of less viscous brine with more viscous CO_2 (viscous fingering) and upward movement of

CO_2 due to gravity (gravity override) from an engineering prospective (Izgec, Demiral, Bertin, & Akin, 2005). One of the important phenomenon which effects on the process of CO_2 sequestration is dissolution of CO_2 in reservoir water which can change the operational and thermodynamic condition. During CO_2 injection, part of the injected CO_2 is dissolved in the aqueous phase and not in direct contact with hydrocarbon, which can be defined as the CO_2 lost to the aqueous phase (Yan & Stenby, 2010). It seems this part of CO_2 has no effects on sweeping process. Although dissolution trapping of CO_2 reduces the risk of CO_2 leakage and the security of the trapping, consequently (Shamshiri & Jafarpour, 2010).

Results show that the solubility has no significant effect on gas production. Figure 6 shows the effect of CO_2 dissolution on condensate production of the reservoir. Figure illustrates that dissolution of CO_2 decreases the cumulative condensate production about 5 percent.

Figure 7 depicts the effect of CO_2 dissolution on cumulative CO_2 production. This figure demonstrates that CO_2 solution decreases the cumulative CO_2 production, considerably (about 98 percent).

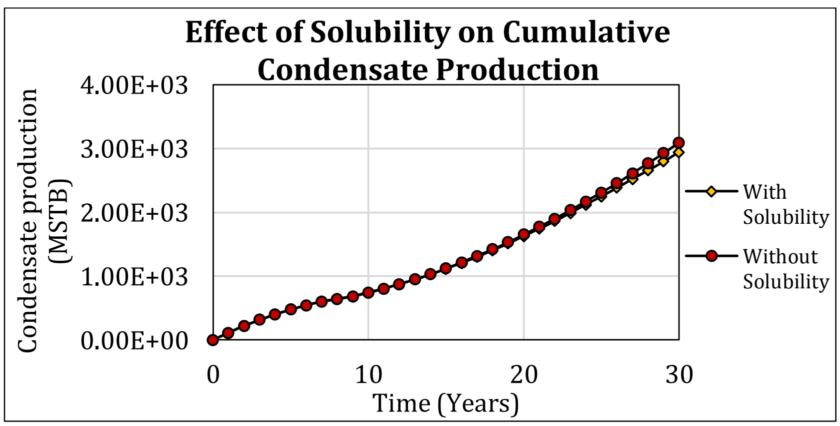

Figure 6. Effect of CO_2 dissolution on cumulative condensate production

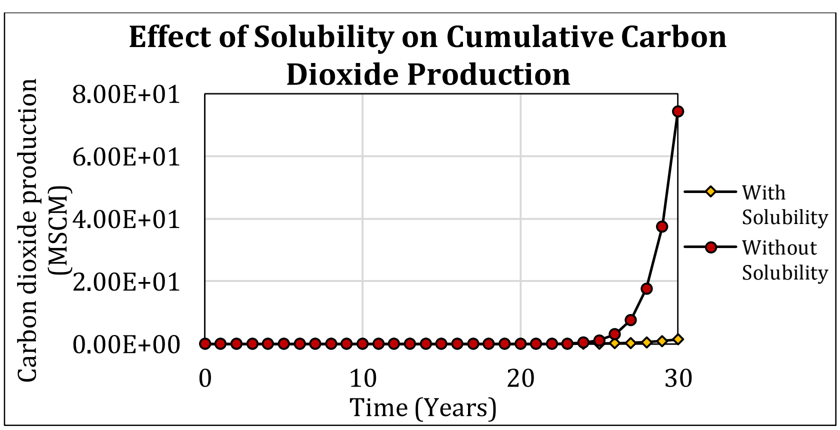

Figure 7. Effect of CO_2 dissolution on cumulative CO_2 production

4.2. Effect of Heterogeneity

The fluid flow within petroleum reservoirs is strongly dependent upon heterogeneity of the rock structure (Vafai, 2005). In addition, the presence of reservoir heterogeneities, such as low-permeability stringers or layering, may reduce gas recovery further (Ahmed & Mckinney, 2005). Heterogeneity of reservoir parameters has crucial effects on CO_2-base gas displacement. In this part the effects of heterogeneity on gas and condensate production was studied. The heterogeneity was applied on reservoir permeability which is the most effective parameter on fluid flow. The heterogeneity of permeability causes variation in fluid movements compared to the equivalent homogenous system (Dawe, 2004). The heterogeneity was measured using Lorenz method which introduce the heterogeneity by the term is called Lorenz coefficient and varies between zero, for a completely homogeneous system, to one for a completely heterogeneous system (Ahmed, 2000; Tiab & Donaldson, 2004).

Figure 8 depicts the ratio of gas and condensate production of heterogeneous system to homogenous system versus Lorenz coefficient. This figure illustrates that increase of heterogeneity decreases hydrocarbon production in compare to homogenous case. It should be noted that in all the cases CO_2 was injected in the reservoir. Also it is important to know that the last points of the plot (Lorentz coefficient of 0.688) represents the channel heterogeneity. Although, presence of heterogeneity decreases the hydrocarbon recovery in compare to homogenous case, the ratio of gas and condensate recovery is still high when CO_2 was injected in the reservoir in comparison with the heterogeneous cases without CO_2 injection as can be seen in Figure 9. This figure compares the hydrocarbon production of heterogeneous cases with and without CO_2 injection.

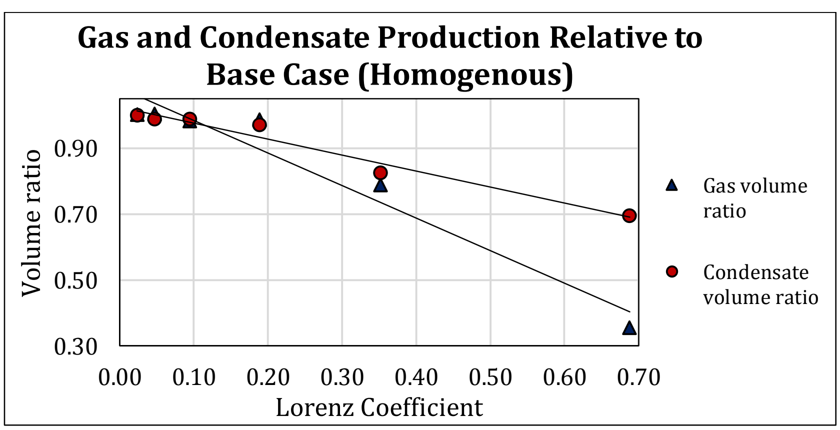

Figure 8. Gas and condensate production relative to base case (homogenous permeability)

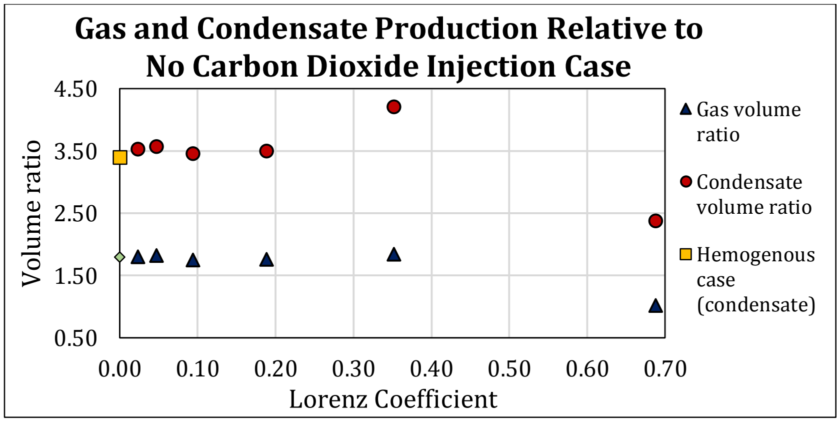

Figure 9. Gas and condensate production relative to no CO_2 injection case

5. Conclusion

In this work the injection of CO_2 to control water invasion of a water-drive gas reservoir was studied. For this aim a cubic compositional simulation model was constructed and three cases of active water-drive, inactive water-drive and active water-drive with CO_2 injection was studied. Then, the effect of CO_2 dissolution and permeability heterogeneity were studied. Considering this work following results can be concluded:

- Injection of CO_2 in a water-drive gas condensate reservoir increases the gas and condensate recovery considerably, without significant amount of CO_2 production. This is because of CO_2 injection prevents the encroachment of water by filling the pore volumes and effective sweeping the reservoir base gas.
- The dissolution of CO_2 in water decrease the effectiveness of sweep efficiency. It decreases the cumulative condensate production. Although, this phenomena has no major effects on cumulative gas production. Although, CO_2 dissolution in water decreases the cumulative CO_2 production, considerably.
- Presence of heterogeneity in the reservoir permeability decreases the effectiveness of the process and decreases the amount of hydrocarbon recovery. Although the amount of hydrocarbon production in compare to no CO_2 injection case are high.

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