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Abstract

The characteristics of tight oil reservoir are low porosity and ultra-low permeability, thus stimulated reservoir volume (SRV) should be conducted whether applying the mode of vertical wells or horizontal wells production. The development effect of tight oil reservoir, CO₂ flooding, and water-alternate-gas (WAG) flooding are compared on the model, several CO₂ flooding and WAG flooding recovery factors are compared. The results of this study show that the recovery factor of horizontal well with SRV is higher than those of horizontal well and conventional fractured horizontal well. The study gives new ideas of CO₂ flooding and WAG flooding in tight oil reservoir.

Keywords: CO₂ flooding; Tight oil reservoir; Gas flooding

Introduction

In recent years, it is become a hot spot to develop unconventional reservoirs, such as tight oil, tight gas and shale gas [1,2]. Tight oil is a typical unconventional resource, which has the characteristics of good fluid properties and poor reservoir properties. The permeability and porosity of tight oil reservoir are general less than 1 and 10%, respectively [3]. Currently, the unconventional reservoirs are usually developed by horizontal wells, especially the segmented multi-cluster fractured horizontal wells, which have been widely used worldwide [4]. The simulated reservoir volume (SRV) can be formed around the horizontal well after segmented multi-cluster fracturing [5,6]. The technology of SRV is to achieve the important goal of increasing the contact area between matrix and fractures or fracture network as far as possible during the development of unconventional reservoirs [7,8]. The study and application of developing tight oil and shale oil reservoirs mostly focus on the natural depletion [9]. But some studies have shown that CO₂ flooding is an effective approach of enhanced oil recovery (EOR) in tight reservoirs [6,10,11]. Based on the real case of Changqing tight oil reservoir in Ordos Basin, both PVT experiments and minimum miscible pressure (MMP) experiments were conducted for the crude oil sample of typical block. The compositional numerical model of typical well-spot well group is built, which is used to study the water flooding, CO₂ flooding and Water-Alternate-Gas (WAG) of CO₂ flooding. Different completion measures of horizontal well are analyzed. Furthermore, parameters such as the formation pressure, production rate, shut-in gas-oil ratio and total gas injection volume are analyzed. "Gas Flooding," also known as miscible flooding, is one of the leading enhanced oil recovery (EOR) technologies employed for recovering oil that was formerly referred to as either stranded or trapped. Gas flooding is an "enhanced oil recovery" application for injecting miscible (and immiscible) gases into an oil reservoir for increasing oil production.

Gas flooding typically includes CO₂ natural gas or nitrogen as the gas that is injected. Gas flooding tasked place as either a miscible or an immiscible flood. Miscible means that the gas that is injected "mixes" with the oil, thereby reducing viscosity and interfacial tension of

the oil and rock. Miscible gas flooding also increases oil "swelling" and localized pressure or drive within the reservoir. "Immiscible" flooding means that the gas that is injected into the reservoir does not mix or go into solution. Therefore the purpose of the immiscible flood is to provide the energy or drive by increased pressure. Immiscible flooding does not produce as much oil as miscible gas flooding, however there are certain applications and reservoirs wherein immiscible flooding is well-suited.

Reservoir Characteristics and Numerical Simulation Model

PVT and MMP experiments

A crude oil sample is obtained in the tight oil reservoir. The PVT experiments are also conducted, and PR3 equation of state (EOS) is applied in PVT regression via PVTi module of Eclipse 2010 to match the experimental data of single flash vaporization test, differential liberation (DL) experiment and constant composition expansion (CCE) experiment. 9 pseudo-components of crude oil are grouped and their mole fractions are shown in Table 1. The parameters are well matched to meet the accuracy required for simulation (Table 2). It illustrates that the critical parameters of fluid can reflect the characters of real reservoir fluid.

Slim tube experiment of the crude oil sample is conducted. The result shows that the CO₂ minimum miscible pressure (MMP) of the crude oil and CO₂ is 19.8 MPa (Figure 1).

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Pseudo-component	CO ₂	N2+C1	C2	& Q &	& &	C7-C10	C11-C17	C18-C27	C28+
Mole fraction (%)			7.83	16.99		10.96		9.62	8.62

Table 1: 3VHXGR FRPSRQHQQVV RI FUXGH RLO VDP SOH

Components	MW(g/mol)	P _c (bar)	T _c (K)	V _c (m ³ /(kg-mol))	Ω _a	Ω _b	AF
CO ₂		73.866				0.078	
N2+C1			203.786	0.098		0.078	
C2	30.070					0.078	0.099
C3+		71.279	339.297	0.221	0.830	0.062	0.169
&		32.621		0.323		0.078	0.260
C7+	120.118					0.132	
C11+			1636.818	0.712		0.132	
C18+			1902.062			0.171	0.093
C28+		39.176		2.187	0.171	0.087	0.183

Table 2: Fluid parameters after regression.

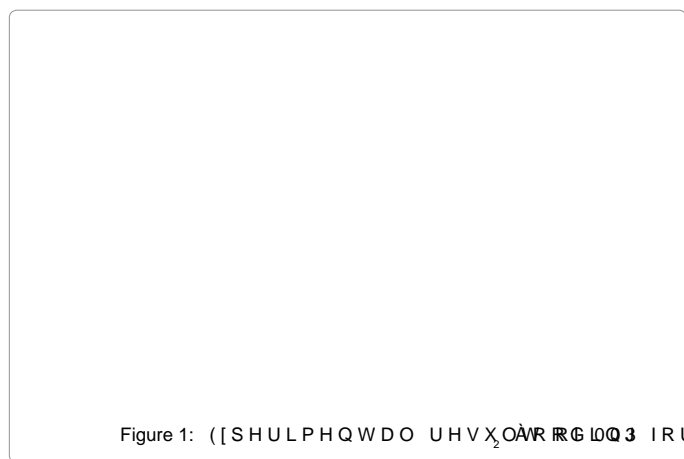


Figure 1: ([SHULPHQWDO UHVX₂O₂AR RG WQ 3 IRU & 2

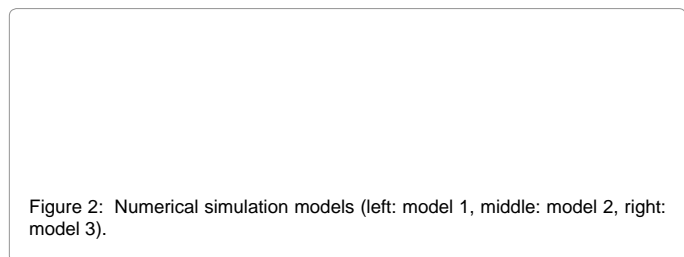


Figure 2: Numerical simulation models (left: model 1, middle: model 2, right: model 3).

Parameters	Value	Parameters	Value
*ULG VSDFL	0.1202	, UUHGXFLEOH ZDWHU VDWXU	0.001
*ULG GLPHQVLRQ		, QLWLDO UHVX ₂ O ₂ AR	0.001
*HRORJLF UHM/HUYH		6DWXUDWLRQ SUHVXXUH	0.03D
Temperature °C	80	, QLWLDO JDV FRLO	0.001
Reservoir depth, m		Oil volume factor	1.297
(IIFWLYH WKLW QHVV 'HPQLW\ RI VXUPDFH RLO		NJ P	
3RURVLW\	8.8	'HQVLW\ RI IRUPDWL	0.001
3HUPDELOLW\ P'		9LVFRVLW\ RI IRUPDWL	0.001
.Y .K	0.1	&RQGXFWLYLW\ RI EL ZLQJ	0.001
, QLWLDO RLO VDWXU	0.001	9LVFRVLW\ RI IRUPDWL	0.001

Table 3: 3DUDPHWHUV RI QXPHULFDO VLPXODWL RLO VDP SOH

Numerical simulation model

Based on the tight oil reservoir, three numerical models of well groups with SRV are built. Model 1, a perforated horizontal well without fracturing located in the middle of the well group and the

length of the horizontal section is 540 m (Figure 2, model 1). Model 2, there are a hydraulic fracturing horizontal well with three bi-wing transverse fractures in the toe, middle and heel of the well, respectively (Figure 2, model 2), and the location and length of model 2 are the same as model 1. Model 3, a 540 m length horizontal well located in the middle of the well group. The horizontal well has been segmented multi-cluster fractured and formed four 100 m x 180 m x 10 m SRVs around the wellbore (Figure 2, model 3). Four vertical wells are located around them for each model. In this paper, the geometry of fracture extension is assumed to be wire-mesh networks, which forms a rule rectangular fracture network after fracturing. In order to guarantee the convergence in simulation and achieve the rectangular fracture propagation, the grids with width of 0.1m are set to fractures. Vertical wells are also volume fractured to increase their injectivity, which is simulated simply by changing the reservoir permeability around them. Detailed parameters of these numerical models are shown in Table 3.

Development Scenarios Optimization

Different completion measures, including perforated completion, conventional fracturing completion and segmented multi-cluster fracturing completion, are analyzed firstly. Then the optimized well group with superior completion are used to optimize different development modes, such as water flooding, successional CO₂ flooding and WAG of CO₂ flooding. Finally, the parameters, including the formation pressure, production rate, shut-in gas-oil ratio and total gas injection volume, are optimized. Evaluation index is mainly the recovery factor of ten years and the CO₂ oil drainage efficiency. CO₂-oil drainage efficiency is calculated by the following equation.

$$E_{CO_2} = \frac{T_{oil}}{T_{CO_2}}$$

Where, E_{CO_2} is CO₂-oil drainage efficiency, which is the reciprocal of CO₂ utilization factor, is total oil production amount (T_{oil} is CO₂ total injection amount (t).

Well completion measures

In order to study the different horizontal well completions impact on development effect, three scenarios are designed. The first scenario is that the horizontal well is completed by perforating. The second scenario is that the horizontal well is completed by conventional fracturing. The third scenario is that the horizontal well is completed by segmented multi-cluster fracturing. The vertical wells are water injection wells,

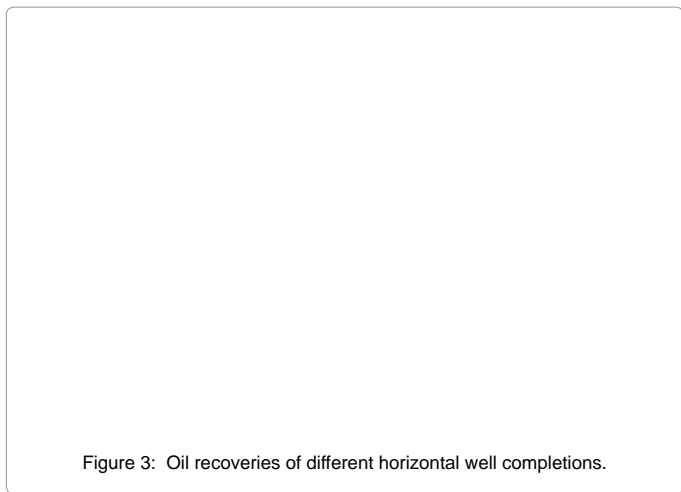


Figure 3: Oil recoveries of different horizontal well completions.

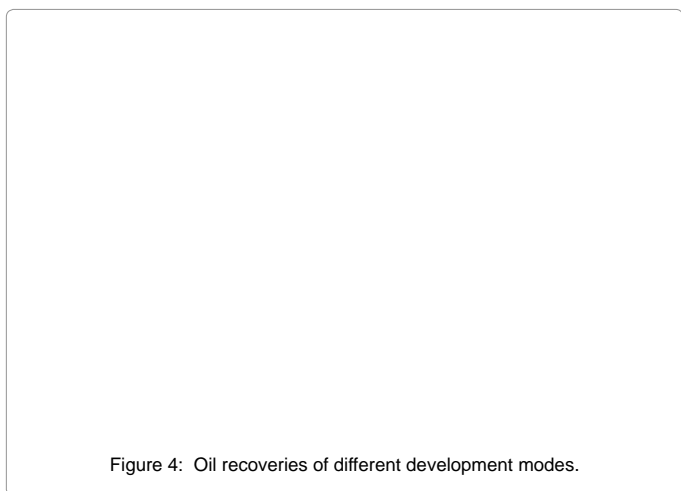


Figure 4: Oil recoveries of different development modes.

the horizontal wells are production wells, and the production control conditions of the three scenarios are the same.

As it can be seen from the Figure 3, the scenario of the horizontal well with SRV has the highest oil recovery, the following is the scenario of the horizontal well with bi-wing fracture, and the scenario of the horizontal well with perforation completion has the lowest recovery. Therefore, the horizontal well with SRV is selected as one of the best well completion measures to develop tight oil reservoir. In the following scenarios, the wells are all volume fractured as wells in model 3.

Development mode

The depletion development mode is usually used to develop tight oil reservoir, which is mainly due to the difficulty in injecting an oil-displacing agent to such tight reservoirs. The vertical and horizontal wells after volume fracturing can obtain SRV around them. The permeability and flow capacity of the reservoir have been greatly improved, which makes it possible to inject an oil-displacing agent to develop tight oil reservoir. Therefore, the water flooding, succession CO₂ flooding and WAG of CO₂ flooding are designed to study their effect on the development tight oil reservoirs. For succession CO₂ flooding and WAG of CO₂ flooding, the same amounts of CO₂ are controlled to inject in these two scenarios.

In Figure 4, the scenario of WAG of CO₂ flooding has the highest oil recovery, while the scenario of water flooding has the lowest recovery.

The oil recovery of WAG of CO₂ flooding is higher than that of the succession CO₂ flooding. One reason is that the same amounts are injected in these two scenarios, and both of them can contribute to oil recover in WAG of CO₂ flooding, but there only CO₂ contribute to oil recover in succession CO₂ flooding. The other reason is that after gas breakthrough, the WAG of CO₂ flooding can control the produced gas-oil ratio better than that of succession CO₂ flooding. Considering obtaining the same recovery, it requires fewer amount of the WAG of CO₂ flooding than that of succession CO₂ flooding, which reduces the cost of gas flooding. Furthermore, the WAG of CO₂ flooding is better to maintain formation pressure and to reduce the produced gas-oil ratio, so it is selected as the best development mode (Figure 5).

Production rate

As the production of horizontal well with SRV is controlled by bottom-hole pressure (FBHP), different production rate can be obtained by adjusting the FBHP. In order to study the impact, 4 scenarios with different FBHP are designed, FBHP of which are 8 MPa, 9.3 MPa, 10 MPa and 12 MPa, respectively.

Figure 6 shows that the higher production rate (the lower the bottomhole pressure) is, the higher the corresponding oil recovery could obtain. But when the FBHP of production well is less than the saturation pressure, the increased of oil recovery is not that obvious, and the CO₂ oil draining efficiency is greatly reduced. Also, the gas breakthrough time would become earlier. Furthermore, it is difficult to maintain the formation pressure around the MMP in the later stage. Therefore the FBHP should not be lower than the saturation, in the other words, the production rate should not be too large. Through the comprehensive analysis of the above, it is preferable to control bottomhole pressure at 9.3 MPa, which is little above saturation pressure (9.25 MPa). When the displacement front reaches the SRV of the horizontal well, the CO₂ starts to breakthrough, then it should be appropriate to increase the water slug to decrease produced gas-oil ratio and maintain formation pressure.

CO₂ injection amount

Based on these following 10 WAG of CO₂ flooding scenarios, the relationship between oil recovery of ten years and injection amount is obtained. Figure 6 shows that injection volume is proportional to the oil recovery, the larger the CO₂ injection amount is, the higher the oil recovery could obtain.

Ensuring adequate CO₂ injection amount is the key to improve oil recovery. Figure 6 shows that oil recovery increases with the increasing of CO₂ injection amount. But when the CO₂ injection amount is larger than 4x10⁴ t, the increase of oil recovery is slow. Therefore, the reasonable total injection amount of 4-4.5x10⁴ t CO₂ is recommended for this five-spot pattern well group.

Conclusion

The permeability and flow capacity of the reservoir have been greatly improved after larger scale SRV measures, which makes it possible to inject an oil-displacing agent to develop of tight oil reservoir. The WAG of CO₂ flooding has better development effect than water flooding or succession CO₂ flooding. The WAG of CO₂ flooding can offset the short comings of low oil displacement efficiency of water flooding, and it can also improve the low sweep efficiency of succession CO₂ flooding. In order to slow down the speed of the CO₂ breakthrough and maintain the formation pressure, it should be appropriate to increase the water

