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Adaptability Analysis of Single-well Water Injection-production Under Different Well Patterns In Ultra-low Permeability Reservoirs

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ABSTRACT

Facing the water-injection difficulty and low oil recovery in ultra-low permeability reservoirs, single-well water injection-production (SWWIP), which transforms water injection between different wells to between horizontal-well fracture stages, was recently proposed as an innovative water-injection approach for EOR. However, SWWIP under some well patterns could cause even worse production performance in development applications. Therefore, this work conducts an adaptability study of SWWIP under common well patterns and aims to find suitable patterns for carrying out SWWIP.

We summarized three kinds of SWWIP modes based on the reported work. An industry-standard reservoir simulator (CMG-IMEX) is used to simulate the production of three modes under five kinds of well patterns, including five-spot, rhombus five-spot, seven-spot, staggered seven-spot and nine-spot patterns. Under the same well pattern, we first compared oil recovery of different SWWIP modes and conventional injection-production mode to find the best/worst modes. Then, based on the best mode, we compared oil recovery of different well patterns to find the optimal pattern.

The results show that the average oil recoveries of mode 1,2,3 and the conventional injection-production mode under five kinds of well patterns are 13.9%, 9.7%, 17.9%, and 12.9%, respectively. Mode 3 is optimal to improve oil recovery. It is demonstrated that the oil recoveries of mode 1 under staggered seven-spot and nine-spot patterns and mode 2 under rhombus five-point, seven-spot, staggered seven-spot and nine-spot patterns are generally lower than conventional injection-production mode. Therefore, mode 1 under staggered seven-spot and nine-spot patterns and mode 2 under rhombus five-point, seven-spot, staggered seven-spot and nine-spot patterns are not suitable for development operation. The results also show that the mode 3 under seven-spot pattern can obtain the highest oil recovery with the same water injection.

Keywords: EOR, single-well water injection-production (SWWIP), well pattern, ultra-low permeability reservoirs

NONMENCLATURE

Abbreviations	
SWWIP	Single-well water injection-production
EOR	Enhanced oil recovery
IFs	Injection fractures
RFs	recovery fractures

1. INTRODUCTION

In recent years, unconventional reservoirs have gradually replaced conventional reservoirs as a new growth source of crude oil production. Especially, with the development of horizontal drilling and multistage hydraulic fracturing (Shelley et al.2017; Tang et al. 2017; Williams and Clarkson 2014; Apte and Lee 2016), the development of ultra-low permeability reservoirs has attracted much attention and become a new hot focus worldwide (Wang et al.2018; Zhang et al.2018; Luo et al.2021).

According to the local instance, five-spot and seven-spot patterns have been widely adopted in ultra-low permeability reservoirs. However, there are still existing some difficulties in the development of ultra-low permeability reservoirs, such as water injection difficulty, slow energy supplement and low oil recovery. Some scholars have put forward an innovative injection-production technology called single-well water injection-production (SWWIP), which can transform the fluid injection between different wells to between different fractures of the same horizontal well (Sharma and Manchanda, 2013; Cheng et al.2017; He et al.2019; Fu et al.2019). Currently, SWWIP mode mainly contains three kinds of common modes: (1) Mode 1: the middle fractures are injection fractures (IFs) and the remains are recovery fractures (RFs), as shown in Figure 1; (2) Mode 2: the outermost fractures are IFs and the remains are

RFs, as shown in Figure 2; (3) Mode 3: IFs and RFs are adjacent to each other, as shown in Figure 3. The relevant literature has proved that SWWIP can reduce the difficulty of water injection and improve the oil recovery in ultra-low permeability reservoirs (Zhu et al.2017; Guo et al.2019; He et al.2019; Kang et al.2021). However, the adaptability of SWWIP modes under different well patterns remains to be determined, and there are existing risks of reducing oil recovery in applying SWWIP to different well patterns.

The purpose of this paper is to study the adaptability of SWWIP modes under different well patterns, which help explore a novel and better injection-production mode, and has a bit of directory significance to development of ultra-low permeability reservoirs. Besides the commonly-used well patterns, other well patterns widely discussed in the theory, including rhombus five-point, staggered seven-spot and nine-spot well patterns were also discussed in the study, as shown in Figure 4.

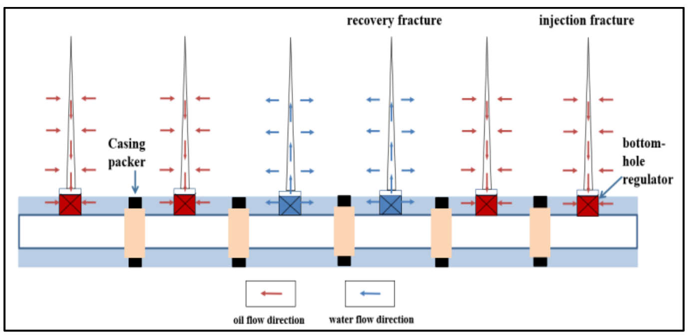

Fig1 SWWIP mode 1: the middle fractures are IFs and the remains are RFs

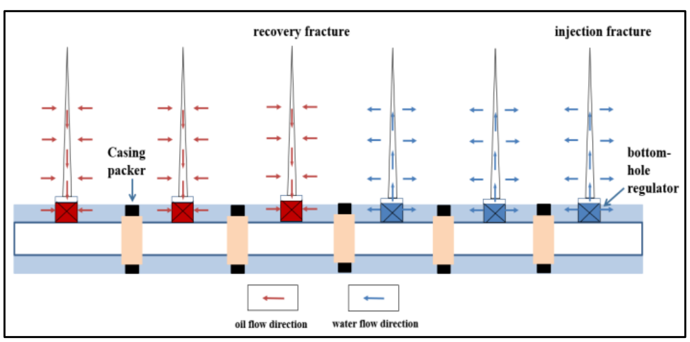

Fig2 SWWIP mode 2: Mode 2: the outermost fractures are IFs and the remains are RFs

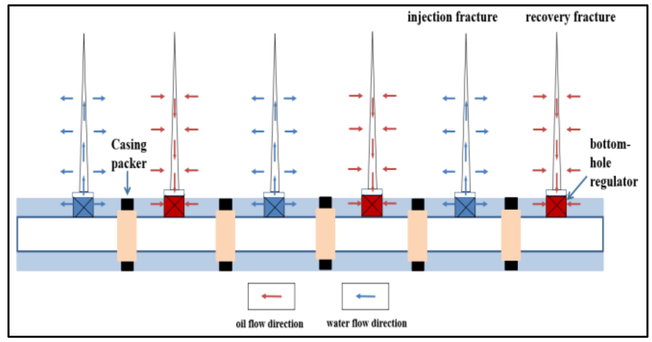

Fig.3 SWWIP mode 3: IFs and RFs are adjacent to each other

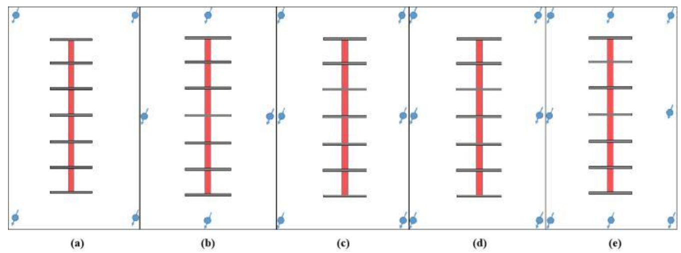

Fig.4 Five kinds of conventional well patterns. (a)five-spot; (b)rhombus five-spot; (c)seven-spot; (d) staggered seven-spot; (e)nine-spot.

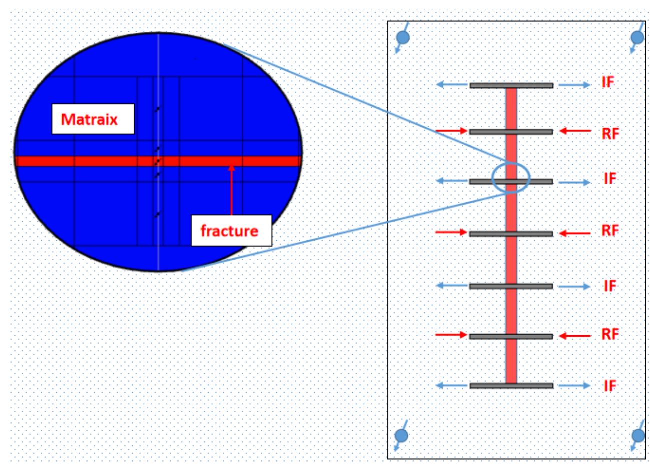

Fig.5 Hydraulic fracturing crack characterized by CMG

2. METHODS

A typical reservoir model with five-spot well pattern is given in Figure 5. We simulated fifteen single-porosity models composed of 5 kinds of well patterns and 3 kinds of SWWIP modes, as shown in Fig 6, 7, 8. The fracture half-length is 328 ft and the hydraulic fracture spacing is 328 ft. The reservoir has initial water saturation of 54% and an initial formation pressure of 2610 psi. The dimension of this computational domain is 197ft (length) × 3937ft (width) × 26ft (height).

The fractures were assigned a conductivity 0.32D•ft. To avoid numerical instability, we used the equivalent fractures with an equivalent fracture half-width of 1 ft and effective permeability of 0.16 D. The domain was composed of 60×100×1 discrete Cartesian grid blocks and we didn't impose flow conditions at all boundaries. The water injection rate of the vertical well was 353 ft^3/d while the iFs of the horizontal well was 706 ft^3/d and the max injection pressure of 5800 Psi. The oil was produced from the RFs of horizontal wells at the max production rate of 883 ft^3/d and minimum bottom hole pressure (BHP) of 580 Psi. We simulated all the injection-production models for 7300 days. The reservoir and operational parameters of the base cases are given in Table 1. An industry-standard reservoir simulator (CMG-IMEX) was used to perform all simulations.

Table 1 Domain properties and reservoir parameters of the base models

Property	Value	Units
Matrix permeability	1.5×10^{-4}	D
Matrix porosity	8.7	%
Hydraulic fracture conductivity	0.32	D•ft
Hydraulic fracture spacing	328	ft
Initial water saturation	54	%
Initial reservoir pressure	2610	psi
Production pressure	580	psi
Injection pressure	5800	psi
Reservoir temperature	163.4	°F
Reservoir depth	7286	ft
Formation compressibility	6.68×10^{-6}	psi^{-1}
Injected fluid	water	N/A
Injection period	7300	days

3. RESULTS

3.1 Base case

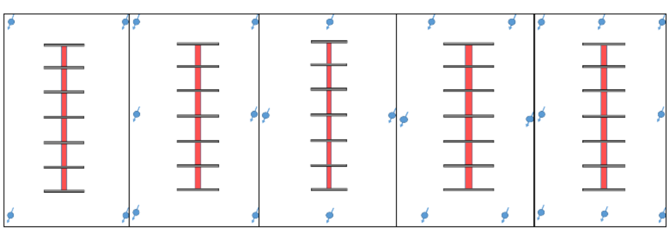

Fig.6 SWWIP mode 1 under five kinds of well patterns. (a)five-spot; (b)rhombus five-spot; (c)seven-spot; (d) staggered seven-spot; (e)nine-spot.

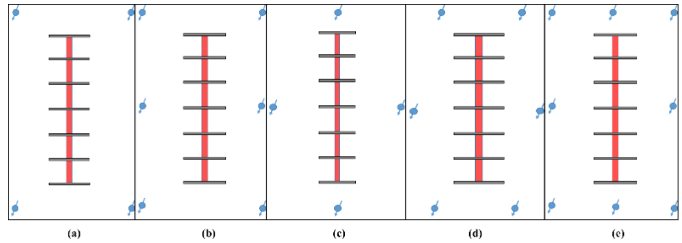

Fig.7 SWWIP mode 2 under five kinds of well patterns. (a)five-spot; (b)rhombus five-spot; (c)seven-spot; (d) staggered seven-spot; (e)nine-spot.

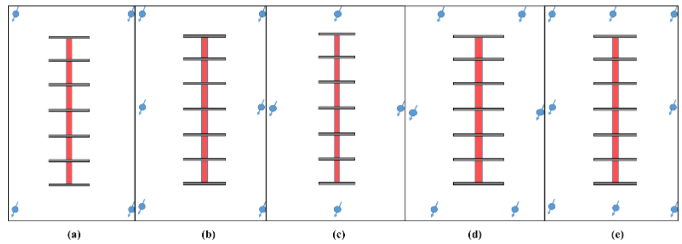

Fig.8 SWWIP mode 3 under five kinds of well patterns. (a)five-spot; (b)rhombus five-spot; (c)seven-spot; (d) staggered seven-spot; (e)nine-spot.

Five conventional injection-production models (Figure 4) were regarded as base cases. Oil recovery was calculated and the oil recoveries of five-spot, rhombus five-spot, seven-spot, staggered seven-spot, nine-spot were 7.8%, 12.4%, 13.2%, 15.2% and 15.6% respectively (Table 2) and the nine-spot well pattern obtained the highest oil recovery.

3.2 Three kinds of SWWIP modes under five kinds of well patterns

Fifteen models were made up of different combinations of three kinds of SWWIP modes and five kinds of well patterns, as shown in Fig. 6, 7 and 8. The oil recoveries of 15 models were calculated for 7305 days water injection. The oil recoveries range from 17.4% to 18.2% for SWWIP mode 3 under five kinds of well patterns, 13.0% to 15.2% for SWWIP mode 1 and 8.4% to 10.7% for SWWIP mode 2 (Fig.9 and Table 2). It can be seen that the oil recoveries of SWWIP mode 3 under 5 kinds of well patterns were much higher than SWWIP mode 1, SWWIP mode 2 and conventional injection modes.

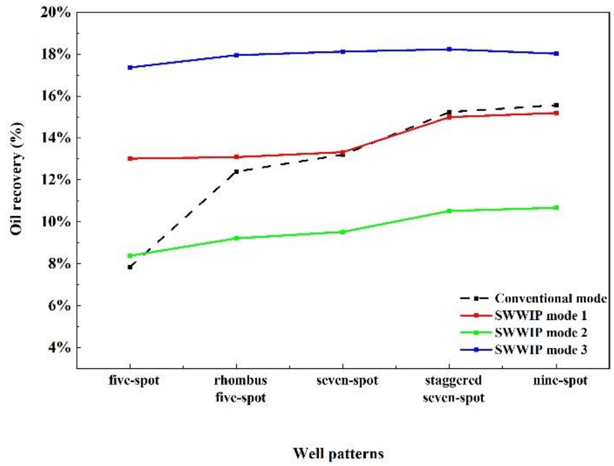

Fig.9 Comparison chart of oil recovery of three SWWIP modes under five kinds of well patterns

Table 2 The oil recoveries of three SWWIP modes under five kinds of well patterns

	five-spot	rhombus five-spot	seven-spot	staggered seven-spot	nine-spot
Conventional mode	7.8%	12.4%	13.2%	15.2%	15.6%
SWWIP mode 1	13.0%	13.1%	13.3%	15.0%	15.2%
SWWIP mode 2	8.4%	9.2%	9.5%	10.5%	10.7%
SWWIP mode 3	17.4%	18.0%	18.1%	18.2%	18.0%

As shown in Figure 10 and Table 3, we should note that the implementation of different SWWIP modes under same well pattern will affect the oil recovery differently. With the implementation of SWWIP mode 3, the oil recoveries under the five well patterns increased by an average of 5.1% compared with the conventional injection-production mode. The five-spot had the highest recovery improvement of 9.5%, while the nine-spot had the minimum increase of 2.5%. For SWWIP mode 1, the oil recovery was improved by 1.1% averagely more than conventional mode. The recovery of SWWIP mode 1 increased under the five-spot, rhombus five-spot and seven-spot well patterns while dropped under the staggered seven -spot and nine-spot. The five-spot well pattern had the best effect of 5.2% increase while the nine-spot had the greatest decrease of 0.4%. For SWWIP mode 2, the oil recovery decreased by an average of 3.2% compared with conventional injection-production mode. The best one is the five-spot which has only increased by 0.5%, while the staggered seven-spot had the biggest decrease of 4.9%.

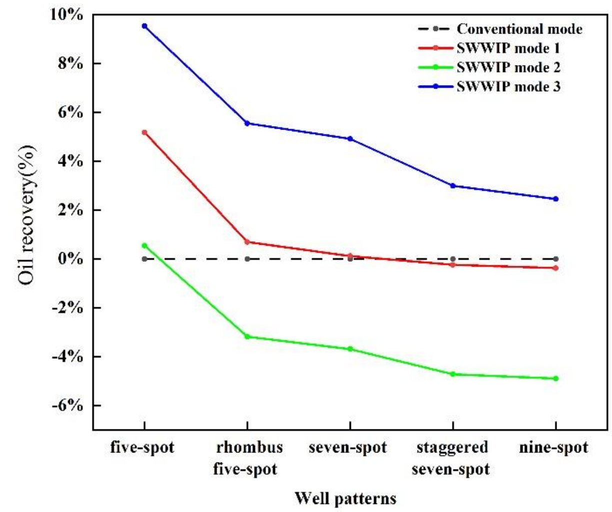

Fig 10 The oil recovery change of three SWWIP modes compared with conventional mode under the same well patterns

Table 3 The oil recovery change caused by the implementation of three SWWIP modes under five kinds of well patterns.

	five-spot	rhombus five-spot	seven-spot	staggered seven-spot	nine-spot
SWWIP mode 1	5.2%	0.7%	0.1%	-0.2%	-0.4%
SWWIP mode 2	0.5%	-3.2%	-3.7%	-4.7%	-4.9%
SWWIP mode 3	9.5%	5.6%	4.9%	3.0%	2.5%

Compared with the conventional injection-production modes, SWWIP mode 3 can improve the pressure gradient between water injection points (water injection vertical well and IFs of the horizontal well) and recovery fractures due to short displacement distance, which can help effectively displace the crude oil near the well and improve oil recovery. The SWWIP mode 1 can lower the difficulty of water injection and reduce the displacement distance to a certain extent, but the displacement distance between fractures is still much greater than SWWIP mode 3, so the effect is not good enough. The implementation of SWWIPM 2 under partial well patterns even brought lower recovery of than conventional injection-production mode. The reason is that the locations of the RFs of the horizontal well were far away from the water injection points, resulting in a longer water injection displacement distance and worse displacement effects (Fig.11). Among the five kinds of well patterns, seven-spot well pattern obtained the highest oil recovery using the same cumulative water injection (0.39PV), as shown in Fig.12.

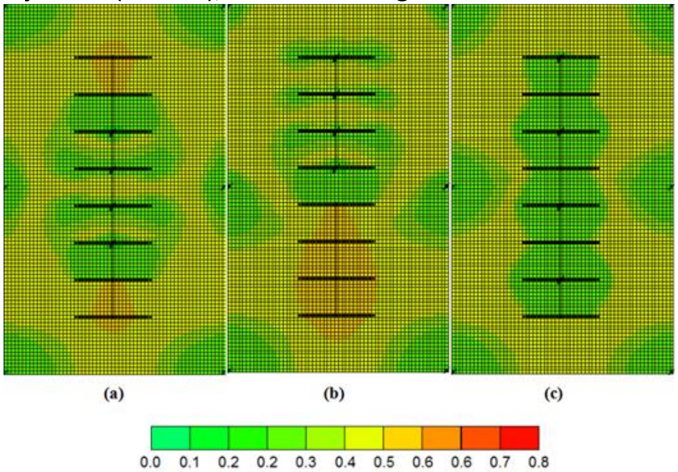

Fig 11 The oil saturation map of three kinds of SWWIP modes under seven-spot well pattern. (a) SWWIP mode 1;(b) SWWIP mode 2;(c) SWWIP mode 3.

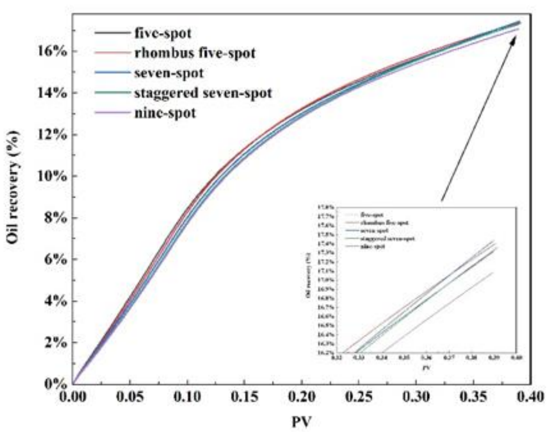

Fig 12 Comparison chart of oil recovery of 5 kinds of well patterns under SWWIP mode 3.

4. CONCLUSIONS

(1) No matter what kind of well pattern is, SWWIP mode 3 has a higher oil recovery than SWWIP mode 1, SWWIP mode 2 and conventional injection-production mode.

(2) In staggered seven-spot and nine-spot well patterns, compared with conventional mode, the oil recovery decreases by 0.2% and 0.4% respectively after implementing SWWIP mode 1. This illustrates that SWWIP mode 1 has poor adaptability to these two kinds of well patterns.

(3) Compared with the conventional injection-production mode, the implementation of SWWIP mode 2 leads to oil recovery descent of 3.2%, 3.7%, 4.7% and 4.9% in rhombus five-point, seven-spot, staggered seven-spot and nine-spot well pattern respectively, suggesting SWWIP mode 2 is less suitable to those four kinds of well patterns.

(4) The SWWIP mode 3 has excellent adaptability to 5 kinds of well patterns. SWWIP mode 3 under 5 kinds of well patterns can achieve an average recovery improvement of 5.1%. SWWIP mode 3 combining five-spot pattern can obtain the largest recovery improvement of 9.5%.

(5) Among 5 well patterns under SWWIP mode 3, seven-spot well pattern obtains the biggest oil recovery under the same cumulative water injection (0.39PV).

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