LOWER LIMITS OF COUPLING PHYSICAL PROPERTIES OF SHALE OIL RESERVOIRS FOR THE APPLICATION OF CO_2 HUFF-N-PUFF

PENG WANG, SHIJUN HUANG & FENGLAN ZHAO
China University of Petroleum (Beijing), China

ABSTRACT

CO_2 flooding for enhanced shale oil recovery is unsatisfactory in pilot projects due to the fracture network complexity induced by gas channelling. CO_2 huff-n-puff has been proven to improve the estimated ultimate recovery (EUR) for a single well. The purpose of this work is to determine the lower limit of coupling physical properties of shale oil reservoirs for the application of CO_2 huff-n-puff technology under different economic and technological development conditions. In this work, a numerical model with two horizontal wells is established to simulate CO_2 huff-n-puff process in shale oil reservoirs. Logarithmically spaced, locally refined, and dual permeability (LS-LR-DK) model is used to generate hydraulic fractures. Then, the critical shifts of hydrocarbon molecules confined in shale nanopores are corrected by a modified Soave–Redlich–Kwong equation of state (m-SRK EOS) to model the phase behaviour accurately. Subsequently, numerical simulations are conducted to investigate the influence of horizontal well length, huff-n-puff cycle, and matrix permeability on well productivity. Finally, the lower limits of coupling the permeability and initial oil saturation are determined in the economic limit output. Longer horizontal well shows a much better performance on improving single-well EUR both in the depletion and CO_2 huff-n-puff stage. There is an optimum injection time for CO_2 huff-n-puff under different reservoir conditions. Determining the lower limit of coupling physical properties in shale oil reservoirs is critical from the perspective of investment income. When the matrix permeability is in the range of 0.01mD to 0.1mD, the performance on improving single-well EUR of CO_2 huff-n-puff is better, and it increases as the initial oil saturation increases.

Keywords: shale oil reservoirs, CO_2 huff-n-puff, lower limits of coupling physical properties, nano-confinement, numerical simulation.

1 INTRODUCTION

With a significant increase in the global energy demand and a gradually declined production of conventional oil reservoirs, unconventional resource has become the focus of researchers [1]. Several studies have demonstrated that the estimated recoverable reserves of shale oil are extremely large, and it has become one of the most potential and important alternative resource [2], [3]. Shale reservoirs have extremely low porosity and permeability resulting from the dominance of nano-scale pores and the heterogeneity of pore structures [4], [5]. Hence, conventional technologies are no longer applicable in shale oil reservoirs. The advancements of horizontal wells and hydraulic fracturing technology have promoted the development of shale reservoirs [6]. There is a high oil production rate during the early age of depletion, but it declines sharply in the succeeding years, and the final oil recovery factor of depletion is generally less than 7% [7]. The main reason is that the supplement of the matrix is difficult to satisfy the production from the complex fracture system. Subsequently, infill drilling technology is practiced to improve shale oil production. Although infill drilling can increase the initial oil production, it can only guarantee a relatively high initial production rate [8]. The CO_2-EOR method is widely used in conventional oil reservoirs, which draws the attention of the researchers for the application on shale oil reservoirs [9]–[11]. Compared with N_2 and CH_4, CO_2 and shale oil are easier to miscible. Amount of numerical simulation and experimental studies indicate that CO_2 injection has high potential for improving shale

www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/EPM220011

oil production and playing the role of CO_2 geological storage [12]–[14]. Unfortunately, due to gas channelling induced by fracture network complexity, and the performance of CO_2 flooding in the field the latter is not ideal [15]. Compared with CO_2 flooding, CO_2 huff-n-puff technology has been demonstrated to be feasible in improving single-well estimated ultimate recovery (EUR) [16], [17]. The research of Kong et al. [18] demonstrated that asynchronous CO_2 huff-n-puff performed much better than a synchronous pattern. However, the lower limits for the application of CO_2 huff-n-puff in shale oil reservoirs by considering coupling physical properties is absent.

In this work, numerical simulation methods are utilized to investigate the performance of CO_2 huff-n-puff in stimulated shale oil reservoirs. Compositional simulator based on the conventional EOS is adopted to establish a numerical model representing the rock and fluid properties of Chang 7 shale oil reservoirs in Ordos basin and simulate the composition change during depletion and CO_2 huff-n-puff. Then, a modified SRK EOS proposed in our previous work is utilized to correct the critical temperature and pressure shifts of shale oil components by considering the adsorption induced confinement effect in shale nanopores. Subsequently, numerical simulations are conducted to analyse the sensitiveness of the horizontal well length, huff-n-puff cycle and matrix permeability. Finally, the lower limits of coupling the initial oil saturation and permeability are determined in the economic limit output.

2 METHODOLOGY

A logarithmically spaced, locally refined, and dual permeability (LS-LR-DK) model is used to establish a numerical model to represent the characteristics of Chang 7 shale oil reservoirs in Ordos Basin. The schematic diagram of the numerical reservoir model is shown in Fig. 1. In the LS-LR-DK model, hydraulic fractures are generated through the equivalent method of fracture conductivity, and a Tartan grid is formed through automatic local logarithmic refined. It can efficiently and accurately establish fracture models, improve the computational efficiency, and accurately simulate the characteristics of transient flow in shale oil reservoirs [19].

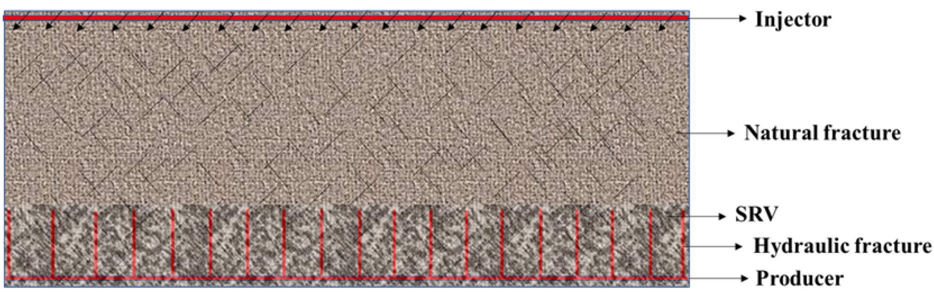


Figure 1: Schematic diagram of the numerical model.

2.1 Numerical model

In this work, a numerical reservoir model is established using the reservoir simulation software developed by Computer Modelling Group (CMG). CMG software has an integrated reservoir simulation framework for unconventional reservoirs to generate the complicated fracture network, forecast future behaviour, and evaluate EOR processes. The dimensions of the numerical reservoir model are 1520 m × 420 m × 12 m, which refer to the length, width and thickness, respectively. A horizontal well is stimulated as a producer, and another horizontal well 400 m away from the producer acts as an injector. In stimulated reservoir volume (SRV), 16 hydraulic fractures are generated, whose fracture spacing and half-length are 100 m and 120 m, respectively. Hydraulic fractures penetrate the numerical reservoir model and their fracture conductivity is 100 mD·m. Other model parameters are provided in Table 1.

Table 1: Other basic parameters of the numerical reservoir model.

Parameter	Value	Parameter	Value
Depth (m)	2,100	Matrix permeability (mD)	0.005
Reservoir temperature (°C)	71.71	Matrix porosity	0.1
Reservoir pressure (kPa)	19,070	Initial oil saturation	0.7

2.2 Fluid model

Under the reservoir conditions, the oil density of Chang 7 oil sample is 722.3 kg/m^3, the gas–oil ratio is 105.05 m^3/m^3, and the saturation pressure is 11,520 kPa. The detailed original oil compositional data is shown in Table 2. To accurately characterize the interaction of CO_2 and oil components and reveal the mechanism of enhanced shale oil recovery of CO_2 huff-n-puff, WINPROP module in CMG software is utilized to establish the fluid model.

Table 2: Original oil compositional data of Chang 7 shale oil sample.

Component	Mol.%	Component	Mol.%
N_2	1.369	iC_5	1.563
CO_2	0.11	nC_5	2.218
CH_4	27.322	C_6	3.515
C_2H_6	8.657	C_7	4.623
C_3H_8	10.051	C_8	3.927
iC_4	1.638	C_9	3.409
nC_4	4.454	C_{10}	2.799
C_{11+}	24.346		

2.2.1 Splitting and lumping

Establishing an accuracy fluid model is a premise for the reliability of a compositional simulation. The compositional simulator is more time-consuming than the black-oil simulator due to more components in original oil composition, but it can more accurately characterize the composition changes during oil production, especially for gas injection. Therefore, it is necessary to split and lump the components for accurately characterizing the fluid phase behaviour and improving the calculation efficiency. Compositional data and binary interaction parameters (BIP) of the fluid model for Chang 7 shale oil sample are listed in Tables 3 and 4.

2.2.2 Modifying the critical property shift

The adsorption induced confinement effect in shale nanopores may alter the fluid thermophysical properties, such as the critical properties. It is crucial to modify the critical

Table 3: Compositional data of fluid model for Chang 7 shale oil sample.

Component	Mol	P_c (atm)	T_c (K)	Acentric factor	MW	SG	Parachor
CO_2	0.0011	72.80	304.20	0.225	44.01	0.82	78.00
N_2-C_1	0.2869	44.86	187.38	0.010	16.61	0.32	75.28
C_2-C_6	0.3210	39.90	395.71	0.171	50.89	0.53	168.45
C_7-C_{10}	0.1476	24.05	576.48	0.410	118.40	0.71	364.42
C_{11}-C_{21}	0.1739	15.41	791.79	0.912	248.62	0.80	559.94
C_{22}-C_{30}	0.0446	9.29	915.44	1.254	393.99	0.86	851.89
C_{31+}	0.0249	6.95	1121.75	1.826	700.71	0.92	1099.14

Table 4: BIP of fluid model for Chang 7 shale oil sample.

Component	CO_2	N_2-C_1	C_2-C_6	C_7-C_{10}	C_{11}-C_{21}	C_{22}-C_{30}	C_{31+}
CO_2	0.000	0.100	0.122	0.115	0.150	0.150	0.150
N_2-C_1	0.100	0.000	0.003	0.013	0.021	0.031	0.041
C_2-C_6	0.122	0.003	0.000	0.003	0.008	0.014	0.022
C_7-C_{10}	0.115	0.013	0.003	0.000	0.001	0.004	0.009
C_{11}-C_{21}	0.150	0.021	0.008	0.001	0.000	0.001	0.004
C_{22}-C_{30}	0.150	0.031	0.014	0.004	0.001	0.000	0.001
C_{31+}	0.150	0.041	0.022	0.009	0.004	0.001	0.000

temperature and pressure shift to model the phase behaviour of nano-confined fluids more accurately. In this section, an m-SRK EOS proposed in our previous work is used to modify the critical property shift of nano-confined fluids; the dimensionless shifts of critical temperature are expressed as following [20]:

$$\Delta T_c = \frac{T_c - T_c'}{T_c} = \frac{\eta(2\psi-1)}{(\psi-1)^2+\eta(2\psi-1)}, \tag{1}$$

$$\Delta P_c = \frac{P_c - P_c'}{P_c} = \frac{2\eta(2\psi-1)(\psi-1)^2+[\eta(2\psi-1)]^2}{(\psi-1)^4+[\eta(2\psi-1)]^2}, \tag{2}$$

where ΔT_c is the critical temperature shift; T_c is the critical temperature, K; T_c' is the critical temperature of nano-confined fluids, K; ΔP_c is the critical pressure shift; P_c is the critical pressure, Pa; P_c' is the critical pressure of nano-confined fluids, Pa; η is relative effective molecular volume coefficient; ψ is fluid distribution coefficient. The detailed process for proposing two analytical formulas of critical property shifts is derived in our previous work. The calculated critical temperature and pressure of nano-confined fluids are shown in Table 5.

After modifying the critical property shift, the calculated values of the fluid model are contrasted with the experimental data of a constant composition expansion (CCE) experiment. As illustrated in Figs 2 and 3, the calculated values of relative volume and oil density for fluid model displays a good agreement compared with the experimental values.

Table 5: Modifying the critical property shift of each oil components.

P_c (atm)	P_c' (atm)	T_c (K)	T_c' (K)
72.80	69.90	304.20	298.08
44.86	43.07	187.38	183.61
39.90	37.85	395.71	385.42
24.05	22.45	576.48	557.00
15.41	14.13	791.79	758.22
9.29	8.36	915.44	868.33
6.95	6.15	1121.75	1054.91

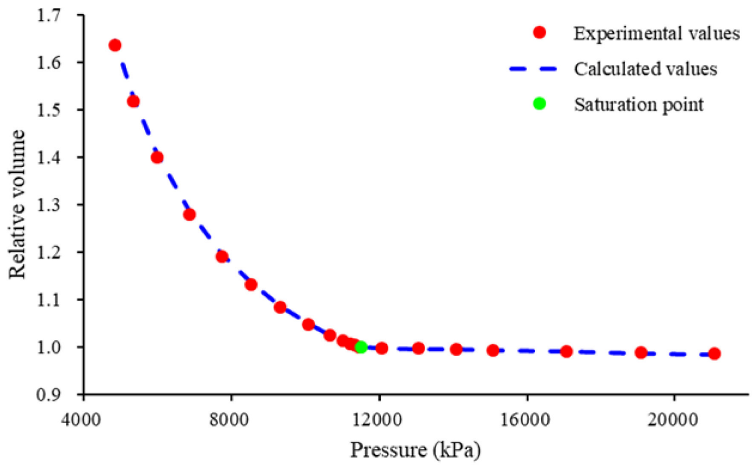


Figure 2: Experimental values and calculated values of relative volume.

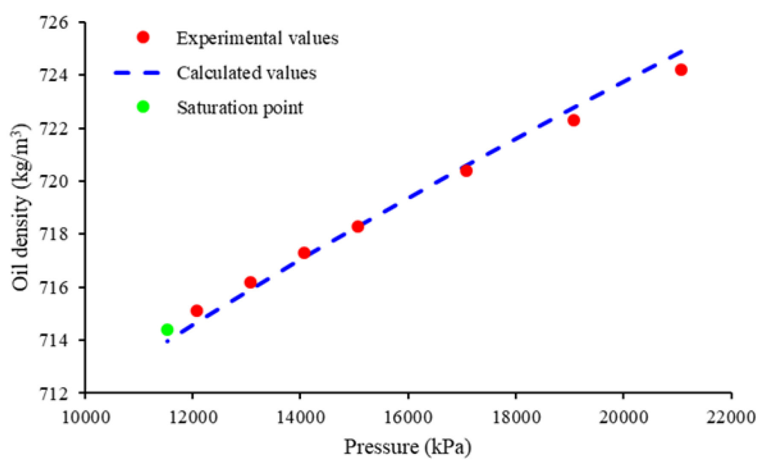


Figure 3: Experimental values and calculated values of oil density.

2.3 CO_2 huff-n-puff process

Based on the numerical model and fluid model of Chang 7 shale oil reservoirs, the huff-n-puff process is simulated to investigate the influencing factor and performance for improving single-well EUR. Depletion, as the primary enhanced shale oil recovery method, is conducted first combining it with hydraulic fracturing technology. Then, the producer is shut in and CO_2 is injected through another horizontal well. Next, the injector is shut in and the soaking stage goes ahead. Finally, the producer is opened to recover the residual shale oil and the process of injection-soaking-production is repeated for a few cycles.

3 RESULTS AND DISCUSSIONS

In this section, sensitivity analyses of horizontal well length, huff-n-puff cycle, and matrix permeability are performed to investigate the influencing factors on improving Single-well EUR for CO_2 huff-n-puff. CO_2 is injected after 10 years of depletion, and the CO_2 huff-n-puff period lasts 10 years. Then, the lower limits of coupling the permeability and initial oil saturation are determined in the economic limit output.

3.1 Effect of horizontal well length

Fig. 4 shows the oil rate and oil recovery factor of producer with horizontal well lengths of 600 m, 1,000 m and 1,500 m. It can be seen from the Fig. 4 that as the horizontal well length increases, the final oil recovery factor increases significantly. During the depletion, the oil recovery factors of producer with different horizontal well lengths (600 m, 1,000 m and 1,500 m) were 3.64%, 5.40% and 6.86%, while the improved oil recovery factors were 2.70%, 3.46% and 3.75% in CO_2 huff-n-puff stage. A longer horizontal well shows a much better performance in shale oil production both at the depletion and CO_2 huff-n-puff stage. In such a poor reservoir condition (0.005 mD), the oil recovery factor is difficult to reach 10% during the depletion, and CO_2 huff-n-puff can play a good role in improving EUR for a single well. From the perspective of the oil rate, it increases as the horizontal well length decreases after well opening in each huff and puff cycle, but it is more difficult to maintain a high oil rate. This phenomenon is related to re-pressurization in the soaking period the shorter the horizontal well length, the higher the re-pressurization after gas injection. When the horizontal well length equals 1,500 m, the maximum oil rate is gradually increasing in the first five huff-n-puff cycle. Extra-low matrix permeability results in a slow sweep

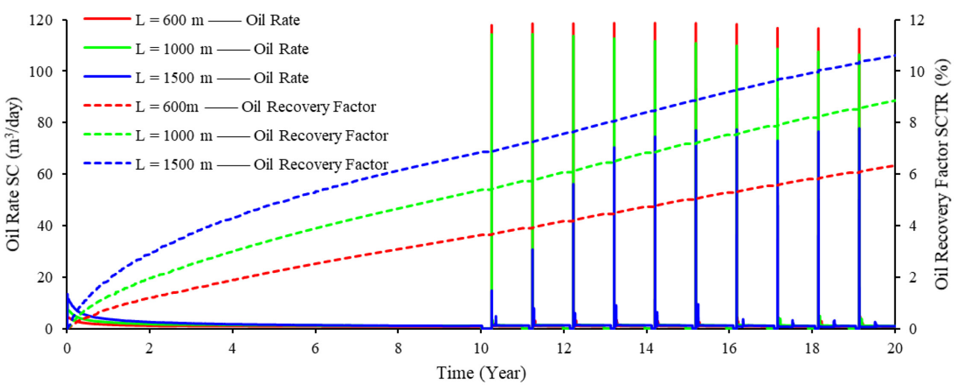


Figure 4: Effect of horizontal well length on the performance of CO_2 huff-n-puff.

efficiency of CO_2 injection. With the increase of huff-n-puff cycles, the larger the swept area of CO_2, the better the performance on improving EUR, and the oil rate remains stable in the last five cycles.

3.2 Effect of huff-n-puff cycles

In this section, the influence of huff-n-puff cycles on improving Single-well EUR is explored. Two scenarios of CO_2 huff-n-puff are adopted that are described in Table 6. Fig. 5 reveals the comparison of CO_2 huff-n-puff with ten and two huff-n-puff cycles on improving Single-well EUR. The performance on improving Single-well EUR of ten huff-n-puff cycles is slightly better than that of two huff-n-puff cycles. On the one hand, the total injection volume of CO_2 with two huff-n-puff cycles is less than that of ten huff-n-puff cycles; on the other hand, due to the extra-low matrix permeability, the injected CO_2 is unswept to SRV resulting in a lower oil rate in the first cycle of scenario 1. The main mechanism for improving Single-well EUR is re-pressurization. It suggests that there are differences in the swept efficiency of CO_2 injection under different geological conditions of shale reservoirs, which will affect the scheme formulation of CO_2 huff-n-puff. Therefore, the effect of matrix permeability on improving Single-well EUR will be discussed in the next subsection.

Table 6: Two scenarios of CO_2 huff-n-puff.

Scenario	1	2
Injection cycle	2	10
Injection period (month)	6	2
Injection rate (m^3/day)	100,000	100,000
Soaking period (month)	3	1
Production period (month)	51	9

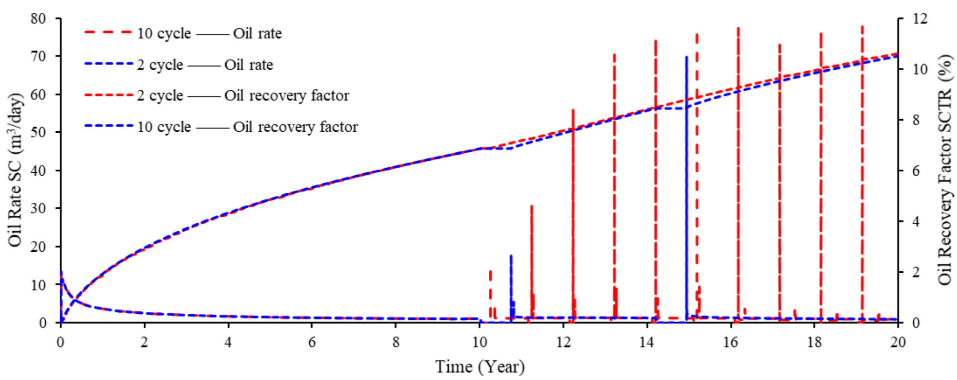
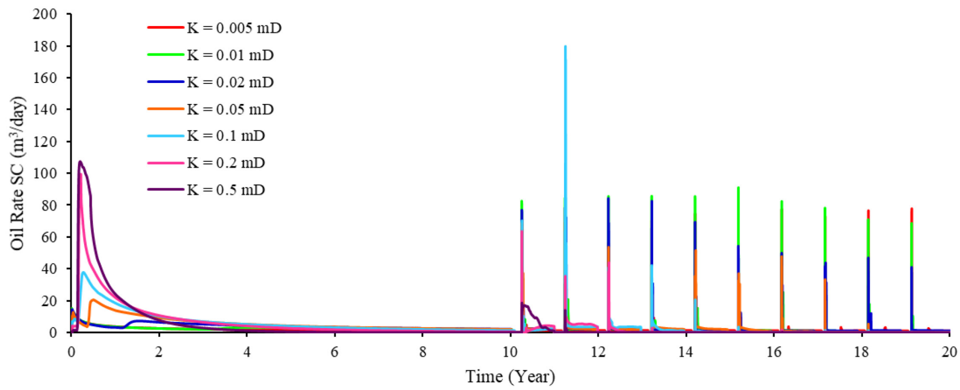


Figure 5: Effect of huff-n-puff cycles on the performance of CO_2 huff-n-puff.

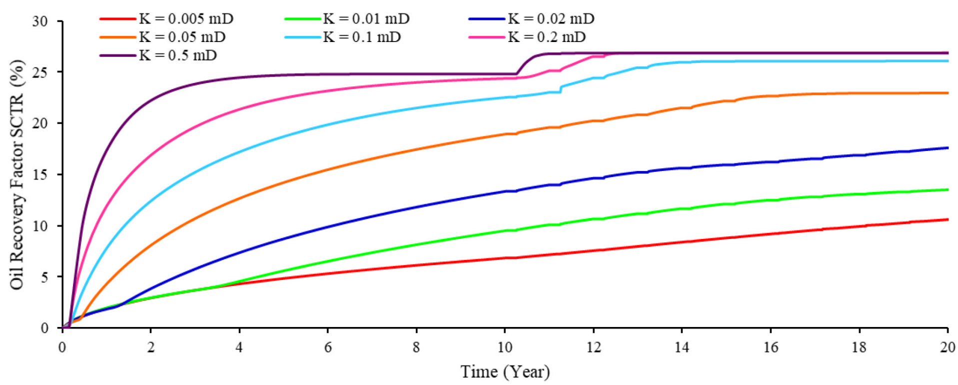
3.3 Effect of matrix permeability

Fig. 6 shows the performance of CO_2 huff-n-puff with different matrix permeability. It can be seen from Fig. 6(a) that the greater the matrix permeability, the greater the maximum oil rate in the initial stage of the depletion, and the shorter the effective huff-n-puff cycle in CO_2

huff-n-puff stage. As depicted in Fig. 6(b), with the increase of matrix permeability, the final oil recovery factor gradually increases. When the matrix permeability is 0.2 and 0.5 mD, the final oil recovery factor is almost identical. In the case of the matrix permeability equalling 0.5 mD, the oil recovery factor remains a constant at around fourth year of the depletion. It indicates that there is an optimized opportunity of CO_2 injection under different reservoir conditions. For the tight reservoirs with a relatively high matrix permeability (0.5 mD), the depletion period can be shortened, and the measures for supplementing the reservoir energy can be adopted as soon as possible to further improve single-well EUR. For the reservoirs with extremely low matrix permeability, multiple huff-n-puff cycles are conducive to improve single-well EUR.



(a)



(b)

Figure 6: Effect of matrix permeability on the performance of CO_2 huff-n-puff. (a) Oil rate; and (b) Oil recovery factor.

3.4 Lower limits of coupling physical properties in the economic limit output

Based on the sensitivity analysis of matrix permeability on the performance of CO_2 huff-n-puff, it appears that there are differences in the applicability and performance of CO_2 huff-n-puff under different geological conditions. Therefore, the lower limits of coupling matrix permeability and initial oil saturation for the applicability of CO_2 huff-n-puff are determined, as shown in Fig. 7. Considering the operation costs such as drilling and fracturing, the lower limits of matrix permeability and initial oil saturation are 0.04 mD and 0.52, respectively, if the single-well EUR need reach 20% to achieve profitability. Fig. 8 is the lower limit during the CO_2 huff-n-puff period under different reservoir conditions. When the matrix permeability is in the range of 0.01 mD to 0.1 mD, the performance on improving single-well EUR of CO_2 huff-n-puff is better, and the oil recovery factor increases as the initial oil saturation increases. When the matrix permeability is greater than 0.1 mD, on the one hand, the residual oil saturation after depletion is low; on the other hand, the gas channelling is considerable resulting in poor performance of CO_2 huff-n-puff. As the matrix permeability is less than 0.01 mD, due to the limited injectability and swept area of CO_2, the re-pressurization plays a primary role in improving the single-well EUR and the performance is poor. Infill drilling might be a potential method by further stimulating the reservoirs near the producer.

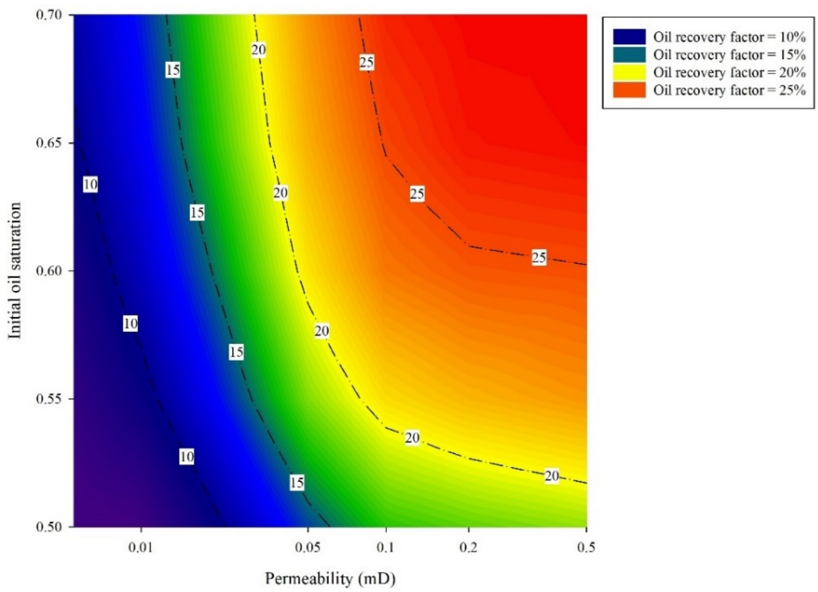


Figure 7: Lower limits of coupling the matrix permeability and initial oil saturation during the whole development.

4 CONCLUSIONS

In this work, numerical simulations are conducted to investigate the influence of horizontal well length, huff-n-puff cycle, and matrix permeability in improving single-well EUR of CO_2 huff-n-puff. Lower limits of coupling the matrix permeability and initial oil saturation are also determined in the economic limit output. The conclusions are as follows:

1. Longer horizontal well shows a much better performance in improving single-well EUR both in the depletion and CO_2 huff-n-puff stage.
2. There is an optimum injection time for CO_2 huff-n-puff under different reservoir conditions. The depletion period can be shortened in tight reservoirs with a relatively

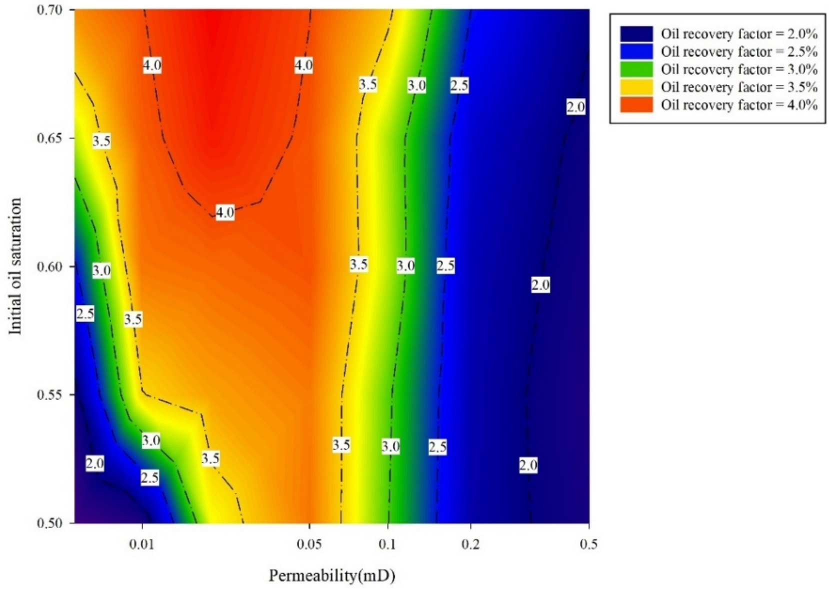


Figure 8: Lower limits of coupling the matrix permeability and initial oil saturation during CO_2 huff-n-puff period.

high matrix permeability (0.5 mD), and multiple huff-n-puff cycles conducive to improved single-well EUR for the reservoirs with extremely low matrix permeability.

3. Determining the lower limit of coupling physical properties in shale oil reservoirs is critical from the perspective of investment income. When the matrix permeability is in the range of 0.01 mD to 0.1 mD, the performance in improving single-well EUR of CO_2 huff-n-puff is better, and the oil recovery factor increases as the initial oil saturation increases. Considering the operation costs such as drilling and fracturing, the lower limits of matrix permeability and initial oil saturation are 0.04 mD and 0.52, respectively, if the single-well EUR need reach 20% to make a profit.

ACKNOWLEDGEMENTS

The authors acknowledge that this work was partially funded by the Strategic Cooperation Technology Projects of CNPC and CUPB (No. ZLZX2020-02-04-04). We also thank the National Natural Science Foundation of China (No. U52174039) for financial support.

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