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Evaluation method for Miscible Zone of CO_2 Flooding

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Abstract: Miscible zone, the area swept by injected CO_2 and its in-situ crude oil miscible with injected CO_2, great effect the oil recovery of CO_2 miscible flooding in reservoir. But there are little published researches on the evaluation method of CO_2 flooding. In this paper, the potential affective factors of miscible zone in CO_2 flooding are analyzed by theory. Dimensionless parameters are used to characterize the potential affective factors. In order to evaluate the miscible zone of CO_2 flooding accurately, published MMP prediction model and reservoir numerical simulation are combined to build its evaluation model in CO_2 flooding based on Box-Behnken design (BBD). And the evaluation method is proposed. The results show that the effect of miscible zone includes less miscibility ability and inhomogeneous pressure distribution. The former is caused by less reservoir pressure and impure injected gas. The latter is caused by inhomogeneous permeability and unreasonable development mode. MMP changes with injected CO_2 volume. The average absolute errors of continue CO_2 flooding and water-alternate-gas flooding calculated by proposed evaluation method are 4.2% and 4.5% respectively. The miscible zone shows a trend of decrease after the first increase with increasing volume of injected CO_2. And the main affective factor of continue CO_2 flooding and water-alternate-gas flooding all are the relative critical temperature of injected gas. The result indicates that the proposed evaluation method can be used to forecast the miscible zone of CO_2 flooding. And the result shows a scientific guidance for further study on CO_2 miscible flooding.

Keywords: *miscible zone, evaluation method, CO2 flooding, MMP*

1. Introduction

Miscibility is achieved when two fluids dissolve with each other and the interface between them vanish because of the function of diffusion and mass transmission (Li and Guo[1]). It is confirmed by theory and practice (Gao[2]; Christensen[3]; Li and Guo[1]; Enick[4]) that the enhanced oil recovery (EOR) of CO_2 miscible flooding is obviously higher than that of immiscible ones. Therefore, CO_2 miscible flooding is an important method for enhancing oil recovery. Its oil recovery of CO_2 miscible flooding is greatly affected by miscible zone whose oil is swept and achieved miscibility. At present, studies on miscible zones (Yuan[6]; Peng, et al[5]; Zhang[8]) mostly focus on slime tube experiment and its numerical simulation. There is especially little study on evaluation method of CO_2 miscible zone with three phases of water, oil and gas. Therefore, in this paper, possible influence factors of CO_2 miscible zone are analyzed. And calculation method of dynamic MMP is combined. Then, evaluation model of CO_2 miscible zone is established by response surface method (RSM), and its changing rule is obtained.

2. Influence factors of CO_2 miscible zone

CO_2 miscible zone is mainly affected by miscibility and pressure distribution in oil reservoir. The former is caused by insufficient reservoir pressure and impure components of injected gas. And the latter is caused by heterogeneity and unreasonable development pattern. Therefore, those problems are deeply analyzed to study the potential reasons to provide theoretical basis for establishing evaluation model of CO_2 miscible zone.

2.1 Miscibility Influence

MMP is the key parameter to evaluate the miscibility of oil and CO_2. MMP coefficient is used to represent the miscibility in this paper. It is defined as the ratio of average reservoir pressure and MMP. Average reservoir pressure is the main influence factor when MMP is constant.

It indicates that the miscible phase can be achieved in the area where CO_2 and oil locate and reservoir pressure is higher than MMP. Miscible degree increases with increasing reservoir pressure (Figure 1). It means that high reservoir pressure is better for achieving miscibility. Based on the definition of MMP coefficient, it can be fined that MMP is the main influence factor of miscibility when reservoir pressure is constant. The influence factors of MMP include reservoir temperature, components of injected gas and oil components.

2.2 Pressure Distribution Influence

Typical non-Darcy flow in low permeability reservoir is shown as follows, (1) existing non-zero threshold pressure gradient; (2) existing nonlinear relationship between flow velocity and pressure gradient when pressure gradient is higher than threshold one; (3) the lower permeability, the higher pressure gradient, and there is a power function relation of threshold pressure gradient and permeability as shown in Figure 2.

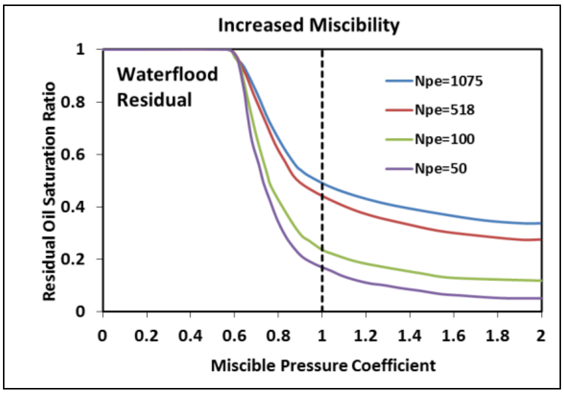

Figure 1 *Curves of residual oil saturation ratio and miscible pressure factor (Ghanbarnezhad and Lake, 2012)*

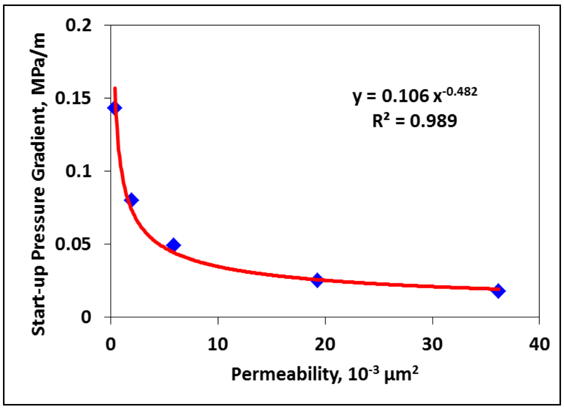

Figure 2 *Relation of start-up pressure gradient and permeability (Zhang et al, 2013)*

In the processing of CO_2 flooding in low permeability oil reservoir, it costs a high pressure drop to overcome threshold pressure in near wellbore zones. The lower permeability, the higher is pressure drop. Low permeability zone is the main performance area of nonlinear effect in heterogeneous formation. The pressure drop in low permeability is higher than that of high permeability in heterogeneous reservoir. It leads to heterogeneous pressure distribution in inter layers. Therefore, the heterogeneous pressure distribution easily leads to heterogeneous miscibility.

Presently, the main method of CO_2 flooding include continue injection and water alternating gas (WAG). The advantage of the former is its high injectivity and quickly energy supplement. But injected CO_2 easily breakthrough that leads to CO_2 channeling. And then, it needs more injected CO_2 to supply formation energy to lower reservoir pressure drop. The advantage of the later includes improving mobility, slowing down fluid-channeling and keeping pressure level. But it reduces the contact between oil and CO_2, and affects miscibility degree of them.

3. Miscible Zone Parameters

3.1 Model Dimensionless Parameters

From the analysis of reservoir characteristic and phenomenon in CO_2 flooding, possible influence factors of miscible zone are obtained, including miscibility degree, injection gas components, permeability heterogeneity and the contact between oil and injected CO_2. Based on the analysis of physics and mechanics, five dimensionless parameters are put forward, which represents the possible influence factors of miscible zone. Miscible pressure coefficient represents miscible degree. Relative critical pseudo-temperature represents the components of injected gas. Permeability heterogeneity coefficient represents formation heterogeneity. Initial oil saturation and dimensionless volume of injection CO_2 represent the contact of oil and injected CO_2. Miscible swept efficiency is used as the dependent variable to represent miscible zone. It is defined as the pore volume ratio of miscible zone and reservoir. Those five dimensionless parameters are shown as equations (1)-(6).

3.2 Calculation method of MMP

The main method in published research (Christensen, 2001; Enick, 2012; Zhou, 2012) to obtain miscible zone is that using MMP of initial crude oil in reservoir and CO_2 as reference. However, multi-contact miscibility of crude oil and CO_2 is a continue process that CO_2 extract light components from crude oil. The oil components in the zone swept by injected CO_2 are dynamically changing with CO_2 flooding. It means that the MMP is changing. Therefore, the MMP of initial crude oil in reservoir and CO_2 is hard to represent practical situation.

Based on the phenomenon of changing crude oil components in CO_2 flooding, a published MMP evaluation model (Liao[16]) is introduced into numerical simulation to calculate the MMP in different time and components. And it can be used to calculate dynamic MMP in time. Its calculation method is put forward as equation (7).

In this paper, crude oil components are divided into ten pseudo-components including N_2, CO_2, C_1, C_2, C_3, C_4, C_5, C_6, $C_{7\text{-}27}$ and C_{28+}. The equation of pseudo-component is shown as equation (8).

The molecular structure and weight of CH4 are unique, and it is plentiful in crude oil, both of these can reduce calculation error. So CH4 is used as the reference to calculate the molecular weight of crude oil. And then the pseudo-molecular weight of C5+ can be obtained based on its mole and mass fraction. The equations are shown in equations (9)-(11).

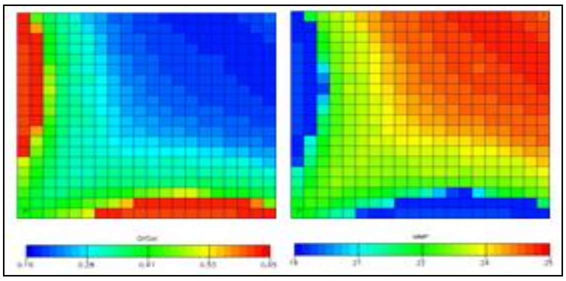

Figure 3 *Distribution of oil saturation and MMP of reservoir in a moment*

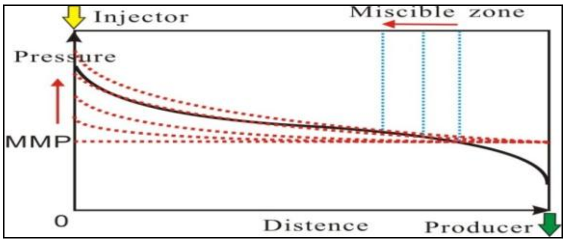

Figure 4 *Schematic diagram of dynamic MMP*

From the MMP distribution in a given time (Figure3), it can be found that the MMP in zones which are steadily swept by injected CO_2 is increasing. Because the light components of crude oil in swept zone are reducing by the continuous CO_2 extraction. And under the situation of keeping reservoir pressure as a constant, some original miscible zones became immiscible zones gradually.

3.3 Box-Behnken Experimental Design

The experiment of response surface analysis is designed based on BBD. It includes five factors and three levels. The five dimensionless parameters are used as the independent variables. CO_2 miscible swept efficiency is the response value. The values of factors and levels are shown in Table 1. The basic parameters are from a typical oil reservoir. Forty-six cases are designed for continuous CO_2 flooding (CCF) and WAG respectively. CO_2 miscible swept efficiency is obtained from each case. All the independent variables and their response values are shown in Table 2.

Table 1 *Data of 5 dimensionless parameters and the levels (CCF and WAG)*

Level	Standard value	P_D	$T_{c,r}$	V_k	S_{oi}	t_D (CCF)	t_D (WAG)
Low	-1	1	0.9	0	0.45	0	0
Mid	0	1.1	1	0.3	0.55	0.6	0.3
High	1	1.2	1.1	0.6	0.65	1.2	0.6

Table 2 *Data of dimensionless parameters and CO_2 miscible swept efficiency of two groups of 46 cases (CCF and WAG)*

Case	P_D	$T_{c,r}$	V_k	S_{oi}	t_D (CCF)	t_D (WAG)	Em (CCF)	Em (WAG)
1	1.1	1	0.3	0.55	0.6	0.3	37.0	35.6
2	1.1	1.1	0.3	0.55	1.2	0.6	11.3	13.3
3	1	1	0.3	0.55	0	0	0	0
4	1.1	0.9	0	0.55	0.6	0.3	2.20	4.40
5	1.1	1	0	0.55	1.2	0.6	24.1	14.9
6	1	1	0.3	0.65	0.6	0.3	24.4	37.2
7	1.1	0.9	0.3	0.55	0	0	0	0
8	1.1	1	0.6	0.55	0	0	0	0
9	1.1	1.1	0	0.55	0.6	0.3	66.0	45.7
10	1	1	0.3	0.55	1.2	0.6	7.80	12.8
11	1.1	1.1	0.3	0.55	0	0	0	0
12	1.1	1	0.6	0.55	1.2	0.6	7.60	13.9
13	1	0.9	0.3	0.55	0.6	0.3	0	0
14	1.1	1	0.6	0.45	0.6	0.3	34.2	38.5
15	1	1	0.6	0.55	0.6	0.3	17.3	25.3
16	1.2	1	0	0.55	0.6	0.3	44.6	66.9
17	1.1	0.9	0.3	0.65	0.6	0.3	0	0
18	1.1	1	0.3	0.65	0	0	0	0
19	1.1	1	0	0.55	0	0	0	0
20	1.1	1.1	0.6	0.55	0.6	0.3	36.4	41.1
21	1.1	1	0.3	0.55	0.6	0.3	37.0	37.6
22	1.1	1	0.3	0.45	1.2	0.6	24.2	7.70
23	1.1	1	0	0.65	0.6	0.3	74.7	65.5
24	1.1	1	0.6	0.65	0.6	0.3	37.2	27.5

25	1.2	1	0.6	0.55	0.6	0.3	53.3	40.9
26	1.1	1	0.3	0.55	0.6	0.3	37.0	38.6
27	1.2	1	0.3	0.55	1.2	0.6	12.5	17.3
28	1.2	1	0.3	0.65	0.6	0.3	57.5	43.7
29	1	1	0.3	0.45	0.6	0.3	23.0	23.4
30	1.2	1	0.3	0.55	0	0	0	0
31	1.1	0.9	0.3	0.45	0.6	0.3	0	0
32	1.1	1	0.3	0.55	0.6	0.3	42.0	38.6
33	1.1	0.9	0.6	0.55	0.6	0.3	0	0
34	1	1.1	0.3	0.55	0.6	0.3	28.2	31.8
35	1	1	0	0.55	0.6	0.3	19.2	51.6
36	1.1	0.9	0.3	0.55	1.2	0.6	0	0
37	1.2	0.9	0.3	0.55	0.6	0.3	2.60	1.70
38	1.2	1.1	0.3	0.55	0.6	0.3	46.4	54.6
39	1.1	1	0.3	0.65	1.2	0.6	17.0	11.5
40	1.1	1	0.3	0.45	0	0	0	0
41	1.1	1	0.3	0.55	0.6	0.3	27.0	38.6
42	1.1	1.1	0.3	0.45	0.6	0.3	43.5	34.1
43	1.1	1.1	0.3	0.65	0.6	0.3	49.7	44.1
44	1.1	1	0	0.45	0.6	0.3	64.7	43.0
45	1.2	1	0.3	0.45	0.6	0.3	38.7	45.4
46	1.1	1	0.3	0.55	0.6	0.3	37.0	30.6

4. Evaluation Model of Miscible Zone

Evaluation model of miscible zone is established by RSM based on the dimensionless parameters and CO_2 miscible swept efficiency. The model is simplified based on variance analysis. The P value of the model is less than 0.0001 which means it has statistical significance. And then, Evaluation model of miscible zone in CCF and WAG is obtained and shown in equation (12) and equation (13) respectively.

The proposed evaluation model is used to forecast CO_2 miscible zones in three typical oil reservoirs in Xinjiang Oilfield, Changqing Oilfield and Jilin Oilfield in China. The result is shown in Table 3. Compared to the result from reservoir simulation, absolute errors of CCF from the proposed evaluation model are 2.6%, 5.0% and 5.1%, 4.2% averagely. Absolute errors of WAG are 3.7%, 5.7% and 4.2%, 4.5% averagely. It indicates that the proposed evaluation model can be used to forecast CO_2 miscible zone.

Table 3 *Basic data and miscible swept efficiency prediction of CO_2 flooding in typical low permeability reservoirs*

Block	**Block B in Xinjiang Field**		**Block A in Changqing Field**		**Block C in Jilin Field**	
Flooding method	CCF	WAG	CCF	WAG	CCF	WAG
V_k	0.37	0.37	0.34	0.34	0.41	0.41
S_{oi}	0.5	0.5	0.47	0.47	0.56	0.56
P_D	1.05	1.05	1.1	1.1	1.07	1.07
$T_{c,r}$	1	1	1	1	1	1
t_D	0.89	0.45	0.89	0.45	0.89	0.45
Em(simulation)	28.1%	28.3%	30.0%	38.8%	27.2%	29.9%
Em(forecast)	30.7%	32.0%	35.0%	33.1%	32.3%	34.1%
Error	2.6%	3.7%	5.0%	5.7%	5.1%	4.2%

5. Changing Rule of Miscible Zone

The sensibility of the five dimensionless parameters about CO_2 miscible swept efficiency is analyzed and shown in Figure 5. It can be found that CO_2 miscible swept efficiency increases with increasing relative critical temperature, miscible pressure coefficient and oil saturation, and reducing with increasing of permeability heterogeneity coefficient. And it is increasing before reducing with increasing of CO_2 injection volume. Based on sensibility coefficients, the sensibility level of CO_2 miscible swept efficiency in CCF and WAG with the dimensionless parameters obtained and shown as follows,

$$\text{CCF: } T_{c,r} > P_D > V_k > t_D > S_{oi}.$$

$$\text{WAG: } T_{c,r} > V_k > t_D > P_D > S_{oi}.$$

The changing rules of miscible zone to the five dimensionless parameters in CCF and WAG are obtained and shown in Figure 6-Figure 9. It can be found that CO_2 miscible swept efficiency increases the increasing of relative critical temperature and oil saturation in the range of reasonable values. And its increase range decreases in high values. Based on MMP evaluation model, it can be found that the increase range of MMP leads the result when relative critical pseudo-temperature less than 1.1. Serious permeability heterogeneity easily leads to CO_2 breakthrough by high permeability channel, which makes CO_2 hard flowing into low permeability zones and mixing with crude oil. And the more serious permeability heterogeneity, the earlier CO_2 breaking through. And it can be found from Figure 9 that CO_2 miscible swept efficiency is little sensitive with oil saturation. Miscible zone increases with the increasing of injected CO_2 volume before CO_2 breaking through. It reaches the peak value at the moment of CO_2 breaking through. After CO_2 breaking through, the MMP of remaining oil increases with continuous exacting of light components by injected CO_2. When its MMP is higher than reservoir pressure, the zone became into immiscible one which leads to the decreasing tendency of CO_2 miscible zone after CO_2 breakthrough.

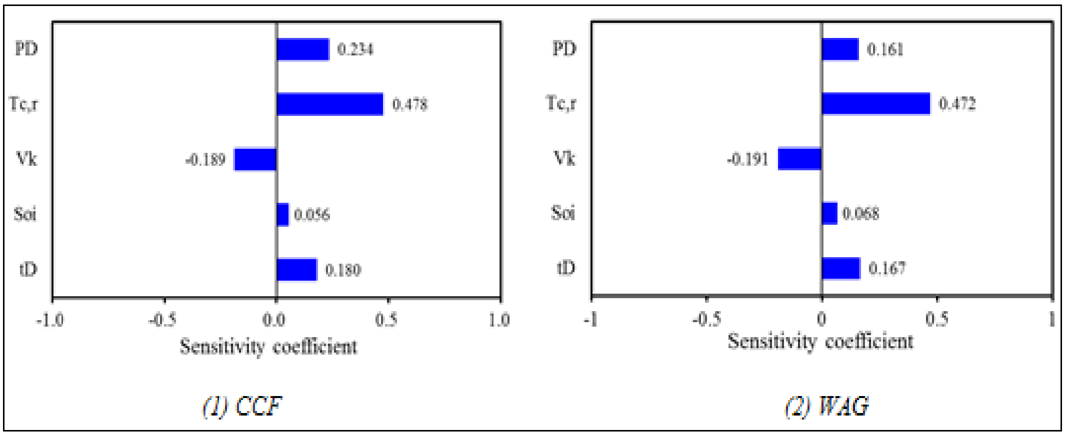

Figure 5 *Sensitivity analyses of the influence factors of miscible zone in CCF and WAG*

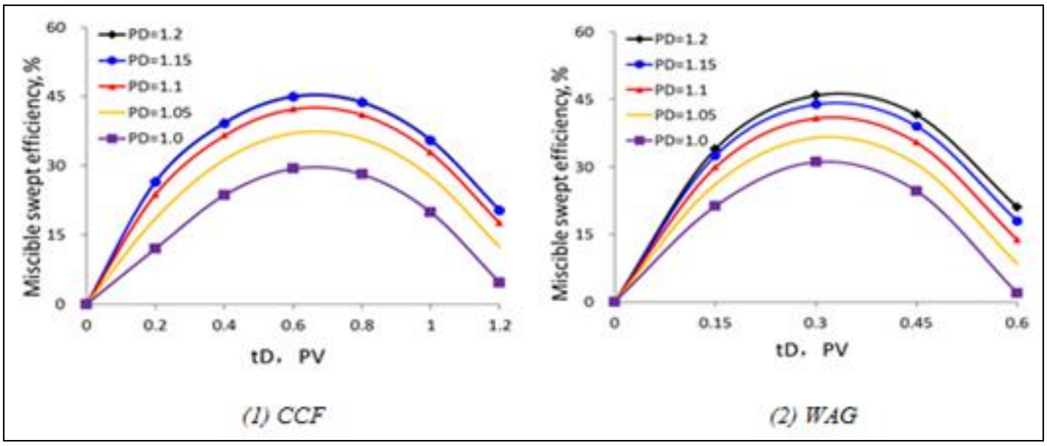

Figure 6 *Curves of CO_2 miscible swept efficiency in different miscible pressure factors*

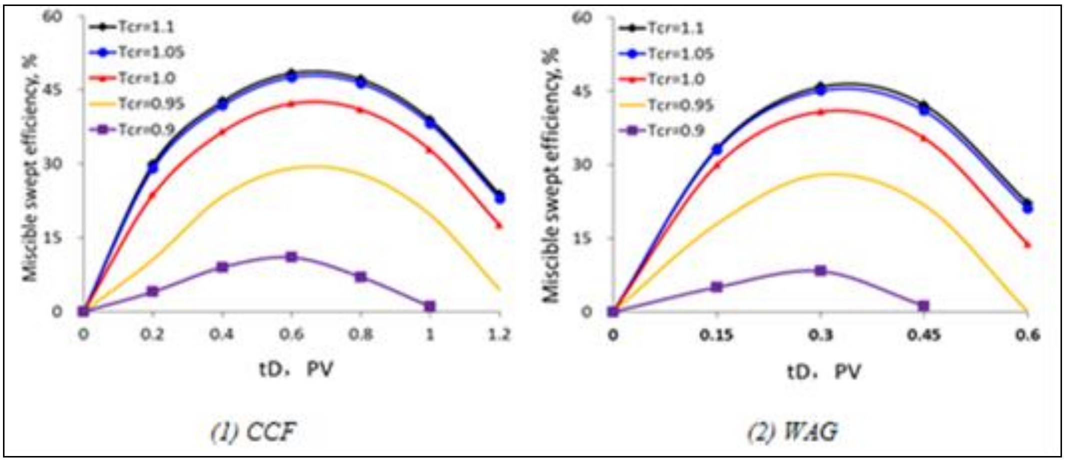

Figure 7 *Curves of CO_2 miscible swept efficiency in different relative pseudo critical temperature*

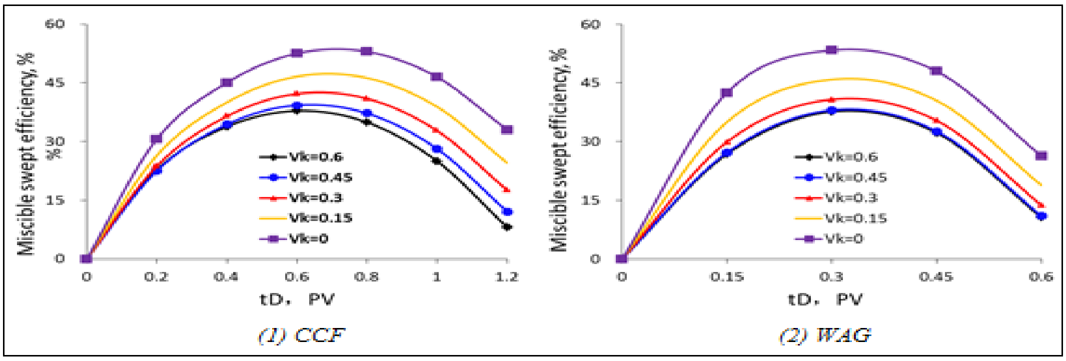

Figure 8 *Curves of CO_2 miscible swept efficiency in different heterogeneity factors*

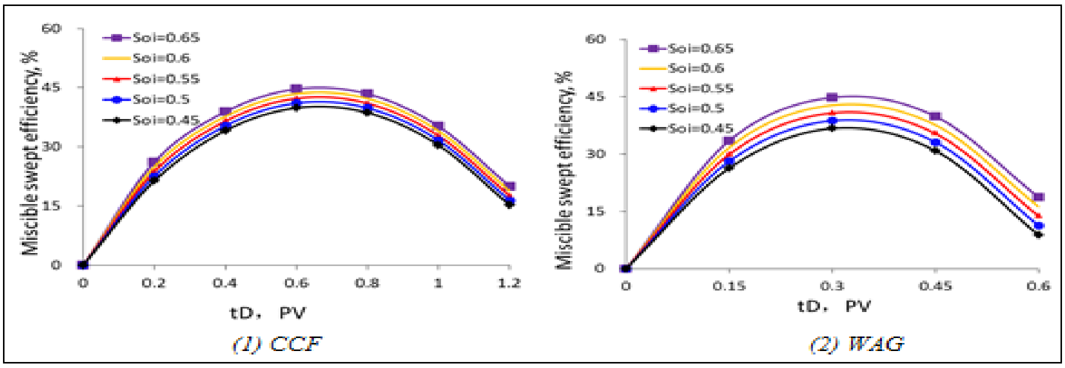

Figure 9 *Curves of CO_2 miscible swept efficiency in different oil saturation*

6. Conclusion

(1) The MMP of crude oil and injected CO2 is changing with the process of CO2 flooding. In the situation of constant reservoir pressure, some miscible zones turn into immiscible ones.

(2) A new evaluation method of miscible zone in CO2 flooding is established based on Box-Behnken experiment design. The low average error indicates that it can be used to forecast miscible zone in CO2 flooding.

(3) The miscible zone shows a trend of decrease after first increasing with increasing volume of injected CO2. And the main affective factors of continue CO2 flooding and water-alternate-gas flooding all are the relative critical temperature of injected gas.

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Equations

(1) $P_D = \frac{P}{MMP}$ Miscible pressure coefficient

(2) $T_{c,r} = \frac{T_{c,p}}{T_{c,CO2}}$ Relative critical pseudo-temperature

Where, P is reservoir pressure, MPa, $T_{c,p}$ is critical pseudo-temperature, ℃, K_i is permeability of layer i, $10^{-3}\mu m^2$, h_i is thickness of layer i, m, V_{inj} is cumulative injected CO_2, m^3, V_Φ is pore volume, m^3, V_m is miscible zone, m^3.

(3) $V_k = 2\int_0^1 \frac{\sum_{i=1}^{m} K_i h_i}{\sum_{i=1}^{n} K_i h_i} d\left(\frac{\sum_{i=1}^{m} h_i}{\sum_{i=1}^{n} h_i}\right) - 1$ Permeability heterogeneity coefficient

Where, MMP is minimum miscible pressure of oil and CO_2, MPa, T is reservoir temperature, ℃, MW_{C5+} is molecular weight of C_{5+}, g/mol, y_{vol} is mole fraction of volatile component, %, y_{int} is mole fraction of middle component, %.

(4) S_{oi} Initial oil saturation

Where, m_i is mole fraction of component i, %, w_i is mass fraction of component i, %, M_i is molecular weight of component i, %, g/mol, M_{oil} is molecular weight of crude oil, g/mol.

(5) $t_D = \frac{V_{inj}}{V_\Phi}$ Dimensionless volume of injection CO_2

(6) $E_m = \frac{V_m}{V_\Phi}$ Miscible swept efficiency

(7) $MMP = 0.003 * T^{0.544} (MW_{C5+})^{1.006} (\frac{y_{vol}}{y_{int}})^{0.143}$

(8) $m_i = \frac{w_i}{M_i} \times M_{oil}$

(9) $M = m_3 \times \frac{M_3}{w_3}$

(10) $WM_{C5+} = \frac{w_{C5+}}{m_{C5+}} \times M = \frac{w_7+w_8+w_9+w_{10}}{m_7+m_8+m_9+m_{10}} \times m_3 \times \frac{M_3}{w_3}$

(11) $\frac{y_{vol}}{y_{int}} = \frac{m_1+m_3}{m_4+m_5+m_6}$

Where, $m_1,\ldots m_{10}$, $w_1\ldots w_{10}$ and M_3 all are given values.

(12) $$E_m = -14.8 + 5.57P_D + 24.4T_{c,r} + 1.51V_k - 7.60S_{oi} + 1.25t_D - 5.03P_D^2 - 14.0T_{c,r}^2 + 0.329V_k^2 - 0.874t_D^2 + 3.90P_D T_{c,r} + 4.35P_D S_{oi} - 1.78T_{c,r}V_k + 3.05T_{c,r}S_{oi} - 0.285V_k t_D$$

(13) $$E_m = -11.5 + 20.8T_{c,r} + 0.288t_D - 2.31P_D^2 - 13.7T_{c,r}^2 + 0.526V_k^2 - 3.61t_D^2 + 6.38P_D T_{c,r} + 1.42P_D V_k - 2.17P_D S_{oi} + 0.712P_D t_D - 1.71T_{c,r}V_k + 2.93T_{c,r}S_{oi} + 1.11T_{c,r}t_D - 0.788V_k S_{oi} + 0.306S_{oi}t_D$$