Energy Proceedings
Vol 35, 2023
ISSN 2004-2965

Ridge Regression Method for Screening CO_2 Flooding Reservoir in Daqing Oilfield

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ABSTRACT

In recent years, the screening criteria for an ultra-low permeability reservoir in the periphery of Daqing Oilfield are not detailed, which leads to the problem of inapplicability of CO_2 flooding. In this paper, a new screening criterion suitable for CO_2 flooding in this ultra-low permeability reservoir is established by using the ridge regression method. Six factors including effective thickness, oil saturation, formation temperature, formation pressure, average permeability and gas injection rate were selected based on the results of CMG numerical simulation, and a total of 30 groups of sensitive factor analysis data were carried out. Then, a ridge regression method for CO_2 flooding was established by using the *t*-value test for the CO_2 flooding potential of an extra-low permeability reservoir in the periphery of Daqing Oilfield. Finally, CMG numerical simulation is used to evaluate the effect of increasing oil production of potential well groups. The ridge regression results show that the oil recovery is sensitive with effective thickness, oil saturation, formation temperature, formation pressure, average permeability and gas injection rate, and their index weights are 0.37, 0.21, 0.15, 0.12, 0.09 and 0.06, respectively. Then, the critical *t*-value are calculated as 0.5 according to the weights, which means that a well group is potential if its *t*-value is above 0.5. According to the above screening criteria, a total of 25 well group in the block are evaluated, and 18 groups are screened as the potential for CO_2 flooding, which accounts for 72% of the block. The CMG simulation results show that the screened well groups contribute an average oil production of 0.36×10^4 t per year, and the annual oil change ratio is more than 0.4, which represents an excellent CO_2 flooding efficiency for this block. The innovation of this study is to use the ridge regression method to evaluate the influence factors on oil recovery of CO_2 flooding, and the calculate results are unique using the regression model. And a screening criterion for CO_2 flooding are then established for this extra-low permeability reservoir.

Keywords: ridge regression, CO_2 flooding, numerical simulation, main control factors

1. INTRODUCTION

The emission of greenhouse gases is regarded as one of the great challenges facing human society in the 21st century [1,2]. It is not only related to the living environment on which human beings depend, but also to the global economic and geopolitical pattern [3,4]. In 2017, the total amount of CO_2 emitted worldwide reached 334.44×10^8 t. China's CO_2 emission is 93.32×10^8 t, accounting for 27.9% of the world's total[5,6]. On the one hand, CO_2 flooding technology can greatly increase oil production and improve economic benefits. On the other hand, it can alleviate the greenhouse gas carbon emission in surrounding coal chemical enterprises. CO_2 oil flooding enhanced oil recovery technology can make up for the shortage of water flooding. Crude oil has good solubility and strong extraction ability, which can greatly reduce the viscosity of crude oil and expand the volume of crude oil. Contacting with formation oil under miscible conditions can effectively reduce interfacial tension and greatly increase oil recovery[7-13]. Block B in

This is a paper for International CCUS Conference 2023 (ICCUSC2023), April 14-15, 2023, Beijing, China.

the Suderte Oilfield is mainly composed of ultra-low permeability (1-10mD) reservoirs[14]. The research block is located in the west of the Suderte structural belt in the Hailar Basin[15], with an area of about 4.5 km^2, this block is rich of oil and gas reserves and has good development prospects, but due to the poor physical properties of the reservoir, it is difficult to establish an effective drive for water flooding. The recovery rate is low, the water injection pressure is too high, and the oil is not effectively produced[16,17]. It is suitable to carry out CO_2 miscible flooding in this block by adopting CO_2 flooding technology according to previous study[18]. The minimum miscible pressure is 16.6 MPa, and the original formation pressure in the test area is 17.6 MPa, which is 1.0 MPa higher than the minimum miscible pressure. However, during the process of CO_2 flooding in the pilot, it was found that with the change of conditions such as temperature, pressure, formation dip angle, etc, the effect of enhanced oil recovery is uncertain, the main controlling factors of CO_2 flooding are unclear, and the principle of influence factors on the oil incremental mechanism is also unclear for this ultra-low permeability reservoir.

Aiming at this block, numerical research were carried out using CMG software to study the main controlling factors of CO_2 flooding, and six factors were considered including effective thickness, oil saturation, formation temperature, formation pressure, average permeability and gas injection rate. In order to build a simple and fast model and speed up the calculation, the ridge regression method was used to judge the mathematical influence of various factors on the CO_2 enhanced oil recovery in this block. Using the regression model, as long as the model and data are the same, unique results can be computed based on the standard statistical method[19,20]. The oilfield data are complex, and the units of different factors are different. Before the calculation of the evaluation value, the data need to be normalized[21-23]. According to the judgment results, the production evaluation of the CO_2 flooding well group in the research block of Daqing Oilfield is carried out to provide theoretical support for the subsequent gas injection production and well selection production.

2. TYPICAL MODEL

2.1 Grid system

According to the development mode of Daqing Oilfield, the GEM component module in the CMG simulation software is selected to conduct numerical simulation research on the main factors of CO_2 flooding at the reservoir scale. According to the characteristics of sedimentary rhythm development, combined with the previous geological research, the theoretical model is divided into 26 sublayers vertically, each sublayer is 1 m thick, and is homogeneous and equal in thickness on the plane. The model adopts an orthogonal grid system, the planar grid step size is 20 m×20 m, and the model grid dimension is 41×35×26=37310. The permeability distribution is shown in Fig.1. The average porosity of each layer is 13%, and the geological reserves of the model are about 25.69×10^4 t.

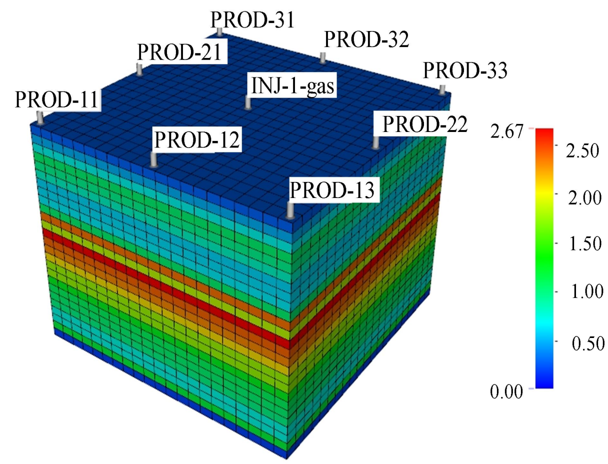

Fig. 1. Permeability of the typical model

2.2 Physical parameters

The density of crude oil under ground conditions in the model is 0.8389 g/cm^3, and the miscible pressure is 16.6 MPa. The theoretical model adopts the oil-water and oil-gas relative permeability curves of low-permeability reservoirs in Block B. The average oil saturation is 44%, the initial temperature is 65℃, and the original formation pressure is 17.6 MPa. The oil phase is fitted with Winprop components. After the components are combined, the mole fractions of each component are: 'CO_2' accounts for 0, 'C1' accounts for 0.0827, 'C_{2+}' accounts for 0.0522, 'C_{4+}' accounts for 0.0289, and 'C_{6+}' Accounted for 0.2208, 'C_{9+}' accounted for 0.2722, and 'C_{11+}' accounted for 0.3432.

3. CALCULATION STEPS

Citing the ridge regression method, the recovery rate in the 30 models was used as the dependent variable and multiple factors as independent variables were used to perform significance calculations. The order of the influencing factors is judged by the size of the significant *t* value, and the index weight is given according to the calculation of the unstandardized regression coefficient b_i. Since the units of each factor in the given reservoir factor design are different, the indicators of each well group need to be normalized before evaluation and scoring.

(1) y is firstly set to be the dependent variable of recovery rate, x_k is the multi-factor independent variable, and when there is a linear relationship between the independent variable and the dependent variable, then the ridge regression model is:

$$y = \sum_{k=1}^{30} t_k x_k + t_0 \qquad (2.1)$$

(2) F value test is then set to as collinearity, the closer the F value is to 1, the better the sample independence.

$$R^2 = \frac{\sum(\hat{y} - \overline{y})^2}{\sum(y - \overline{y})^2} \qquad (2.2)$$

$$F = \frac{R^2 / k}{\left(1 - R^2\right) / n - k - 1} \qquad (2.3)$$

In the formula, y is the actual value, $\overline{y}$ is the average value, $\hat{y}$ is the estimated value, and F is the test value of the K_{th} reservoir model.

(3) Then the significant value t_i of the regression equation can be calculated as follows:

$$t_{\mathrm{i}} = \frac{b_{\mathrm{i}}}{s_{\mathrm{bi}}} \qquad (2.4)$$

In the formula, b_i is the regression coefficient, and s_{bi} is the standard deviation of the regression coefficient.

(4) The reservoir indicators are then normalized. Assuming that there are l oil reservoirs, each oil reservoir can take m items of indicators, and the j_{th} item index of the k_{th} oil reservoir is $X'_{\mathrm{k,j}}$.

$$X_{\mathrm{k,j}} = \frac{\left|X'_{\mathrm{k,j}} - X^*_{\mathrm{w,j}}\right|}{\left|X^*_{\mathrm{o,j}} - X^*_{\mathrm{w,j}}\right|} \qquad (2.5)$$

In the formula, the maximum value $Y^*_{\mathrm{o,j}} = Y^*_{\mathrm{n,j}}$, the corresponding index value $X^*_{\mathrm{o,j}} = X^*_{\mathrm{n,j}}$; the minimum value $Y^*_{\mathrm{w,j}} = Y^*_{\mathrm{1,j}}$, the corresponding index value $X^*_{\mathrm{w,j}} = X^*_{\mathrm{1,j}}$.

(5) The evaluation value of well group k is as follow:

$$T_{\mathrm{k}} = \sum X_{\mathrm{k,j}} \times P_{\mathrm{j}} \qquad (2.6)$$

In the formula, $X_{\mathrm{k,j}}$ is the reservoir geological data after normalization processing, and P_{j} is the weight value of the j_{th} index calculated by the analytic hierarchy process.

Using the above theories and the obtained results, it is possible to evaluate and calculate the suitability of CO_2 flooding reservoirs for all well groups in the entire ultra-low permeability reservoirs. Sorted the calculated evaluation values of all the well groups, and use the evaluation value of 0.50 as the limit to calculate the suitability for CO_2 flooding.The potential assessment of CO_2 can finally be determined for the ultra-low permeability in the periphery of Daqing Oilfield.

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Ridge regression calculation

The calculation results of 30 models are as shown in Fig.2. The greater the effective thickness of the formation, the worse the effect of enhanced oil recovery. The effective thickness of the formation increases from 6 m to 56 m, and the recovery factor decreases from 52.26% to 18.27%. The impact is the most obvious, followed by oil saturation. When the saturation increases from 44% to 74%, recovery increases from 19.40% to 32.68%. The impact of formation temperature and pressure on recovery is as follows. Because the higher the temperature and the lower the pressure, the lower the viscosity of crude oil, the greater the solubility of CO_2 in crude oil, the easier it is to be miscible, resulting in a better CO_2 flooding effect. The effect of CO_2 gas injection rate on enhanced oil recovery is as follows, the recovery rate is 14.80% at 0.2×10^4 t/year, and 20.23% at 1.6×10^4 t/year, however when the gas injection rate increases to 1.0×10^4t/year, the oil increase effect is not significant. When the average permeability increased from 0.1mD to 1.2mD, the recovery increased from 2.29% to 26.8%, however when it increases to 10mD and 50mD, the recovery decreased to 19.67% and 18.86%. The greater the permeability, the better the fluidity of gas, but when the permeability is too high, the breakthrough time of CO_2 will be too early, the contact time with crude oil will be too short, and the advantages of gas flooding will not be fully utilized.

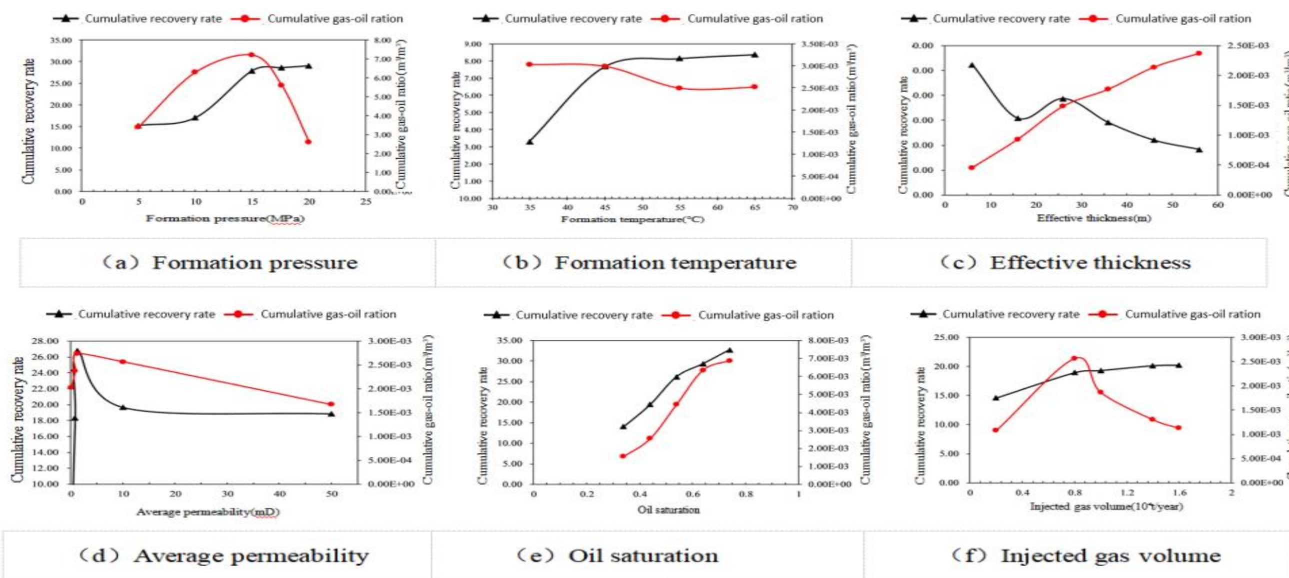

Fig. 2. Typical model calculation results of CO_2 flooding in the typical model

As shown in Table 1, the *F* values between the samples are all close to 1, indicating that the 30 regression models are independent and will not cause collinearity. It can be seen from the significance value that the main factors affecting the enhanced recovery of CO_2 flooding are effective thickness, oil saturation, formation temperature, formation pressure, average permeability, and gas injection rate, the regression coefficient b_i value can also be determined as shown in Table 1, and the index weights are respectively 0.37, 0.21, 0.15, 0.12, 0.09 and 0.06.

Table 1 Ridge regression results calculated from the CMG model

Factor	t_i	b_i'	b_i	F	Weight	Order
Effective thickness	-3.88	-32.38	-0.54	1.000	0.37	1
Oil saturation	2.17	18.69	0.30	1.002	0.21	2
Formation temperature	1.62	9.70	0.22	1.014	0.15	3
Formation pressure	1.29	9.09	0.18	1.011	0.12	4
Average permeability	0.92	7.95	0.13	1.003	0.09	5
Gas injection volume	0.65	5.60	0.09	1.000	0.06	6

Considering the various values of these six indicators, the cumulative gas-oil ratio has not reached the economic limit of 0.2, so the recovery is used as the main reference standard to determine the optimal value and the worst value in the normalization formula, and the values of the optimal value and the worst value used in the normalization of each index are shown in Table 2. The optimal value and the worst value are very important parameters in the normalization process, and their selection has a great influence on the normalization result. Therefore, in order to ensure the accuracy and rationality of the normalized results, their selection must be based on the actual data characteristics and requirements.

Table 2 Optimal and worst value used for the normalization

Index	Worst value	Optimal value
Oil saturation	0.34	0.74
Formation temperature (℃)	35	65
Effective thickness (m)	56	1
Reservoir depth (m)	328	1312
Average permeability ($\times10^{-3}\,\mu m^2$)	0.1/50	1.2
Gas injection volume of CO_2 single well ($\times10^4$ t/a)	0.2	10

4.2 Evaluation of mine production effect

In order to the convenience of refined management in the production process of the pilot, Block B of Daqing Oilfield is divided into 4 sub-blocks. Block SU12 is the earliest pilot block for gas injection. As of February 2022, gas injection has been operated for about 10 years , Blocks B1, B2, and B3 are expanded blocks that started gas injection in November 2016. And as of February 2022, gas injection has been operated for about 6 years.

The scoring results of the ridge regression method are shown in Table 3. SU12 block has the largest producing reserves of 330×10^4 t and the largest effective reservoir thickness of 37.3 m. The well group is the center and is bordered by surrounding well groups with an annual output of about 0.30×10^4 t. Block B1 has the third largest producing reserves of 150×10^4 t, and the largest effective reservoir thickness is about 50 m. Among them, the X56-48 well group and the X50-46 well group have the best development effects, with annual oil production of 0.30×10^4 t and 0.38×10^4 t. The geological characteristics of the B2 block are similar to those of the B1 block, in which the oil saturation around the X42-52 well group decreases most obviously, and the annual oil production is 0.14×10^4 t. Block B3 has the second largest producing reserves of 292×10^4 t, and the largest effective reservoir thickness is 64.2 m. The oilfield development is mainly centered on the X68-66 well group, X70-68 well group and X72-66 well group. The annual oil production is about 0.5×10^4 t. In the evaluation of the effects of the above development well groups, accord to the results ridge regression screening evaluation in the periphery of Daqing Oilfield, the corresponding high-resolution well groups are X58-58 well group with a value of 0.77, X68-66 well group with a value of 0.65, X50-46 well group with a value of 0.58 and X42-52 well group with a value of 0.55, and the corresponding annual oil change rate is 58% , 51%, 46% and 45%, respectively.

Table 3 Comparative of reservoir characteristics in the block

Well group	Annual gas injection volume (10^4 t/year)	Annual oil production (10^4 t/year)	Annual oil change rate	Score
Su12-X54-54	0.79	0.29	37%	0.51
Su12-X54-58	0.87	0.31	36%	0.47
Su12-X58-54	1.14	0.38	34%	0.48
Su12-X58-58	1.07	0.62	58%	0.77
Su12-X62-56	0.91	0.33	36%	0.58
Su12-X62-60	1.31	0.46	35%	0.71
Su12-X64-54	1.02	0.35	35%	0.52
Su12-X66-56	1.23	0.42	34%	0.61
Su12-X66-60	0.63	0.25	40%	0.55
B1-X50-46	0.82	0.38	46%	0.58
B1-X52-48	0.83	0.31	37%	0.50
B1-X52-50	0.78	0.30	38%	0.52
B1-X56-48	0.79	0.30	38%	0.52
B2-X42-52	0.31	0.14	45%	0.55
B2-X43-49	0.16	0.10	63%	0.47
B2-X44-53	0.11	0.05	45%	0.47
B2-X46-55	0.24	0.13	60%	0.53
B2-X48-53	0.25	0.13	56%	0.48
B3-X66-64	0.87	0.31	35%	0.47
B3-X68-66	1.11	0.57	51%	0.65
B3-X70-68	1.59	0.53	33%	0.64
B3-X72-66	1.30	0.44	34%	0.59
B3-X74-68	0.76	0.28	37%	0.50
B3-X75-70	0.72	0.27	37%	0.48
B3-XX73-68	0.83	0.32	38%	0.63

According to the geological date of the pilot, the formation pressure of sub-blocks can reach the minimum miscible pressure of 16.6 MPa. Among all the evaluation indicators, the weight of effective thickness, oil saturation and formation temperature is relatively large, compared with the actual production stimulation measures of the oil reservoir. For well groups with an annual oil change rate of more than 50% and an evaluation value of more than 0.65, CO_2 injection production in the later stage can consider increasing the gas injection rate for well groups with a small gas injection rate. The annual oil change rate is between 40% and 50%, the well group whose evaluation value is below 0.60, and the production well group without gas should be injected stably and reasonably. For well groups with an annual oil change rate between 30% and 40% and an evaluation value below 0.50, it is considered that the Su12 block has been exploited for gas injection for 10 years. For the production well groups that have been with gas breakthrough, the injection ratio should be reduced to control the gas injection. The example shows that the evaluation results of the reservoir ridge regression method are consistent with the actual production history of the research block, which further verifies the guiding significance and rationality of the evaluation method established in this paper.

5. CONCLUSIONS

Based on the results of CMG numerical simulations, a screening criterion for CO_2 flooding are using a ridge regression method for an extra-low permeability reservoir in the periphery of Daqing oilfield. And the main conclusions can be summarized as follows.

(1) The greater the effective thickness of the formation, the worse the effect of enhanced oil recovery. The greater the oil saturation, the better the effect of gas injection to enhance oil recovery. The higher the temperature and pressure, the lower the viscosity of crude oil, the greater the solubility of CO_2 in crude oil, the easier miscibility occurs, and the better the CO_2 flooding effect. During CO_2 gas flooding, the greater the permeability, the better the fluidity of the gas, but if the permeability is too high, the breakthrough time of CO_2 will be too early.

(2) From the t_i value of the ridge regression calculation results, it can be seen that the order of the factors affecting CO_2 flooding enhanced oil recovery is effective thickness, oil saturation, formation temperature, formation pressure, average permeability and gas injection rate.

(3) With the evaluation value of 0.50 as the boundary, the CO_2 flooding potential of the studied block can be evaluated through statistics. The annual oil

change rate of 72% of the well groups in the studied block is about 40%, the evaluation value of 76% of the well groups is above 0.50, and more than 70% of the well groups are suitable for CO_2 flooding to enhance oil recovery.

ACKNOWLEDGEMENT

Thank you to the CCUS Organizing Committee for providing a high-quality display platform. Thank you to the colleagues who helped me during the writing of the paper. Thank you to my family for always understanding and supporting me.

DECLARATION OF INTEREST STATEMENT

I declare that none of the authors involved above have known competing financial interests or personal relationships. It is unlikely to affect the work reported in this article. All authors read and approved the final manuscript.

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