A well selection method of CO_2 huff and puff in heavy oil reservoir with edge and bottom water based on water cut

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Abstract. The water cut of heavy oil reservoir with edge and bottom water rises rapidly and the recovery degree of crude oil is low. CO_2 huff and puff is an effective measure to improve the recovery of this kind of reservoir, and scientific well selection is the premise of the measure effect. Because the existing well selection methods of CO_2 huff and puff in heavy oil reservoir with edge and bottom water mostly take the oil increase of oil well as the evaluation index, ignoring the characterization of well water cut after huff and puff, it is unable to accurately screen all potential wells. Therefore, a quantitative well selection method of CO_2 huff and puff in heavy oil reservoir with edge and bottom water based on water cut is proposed. The method is based on fuzzy comprehensive evaluation theory and analytic hierarchy process, and takes the water cut after CO_2 huff and puff as the evaluation index. Several groups of typical models are designed to screen the sensitive factors and laws of CO_2 huff and puff well selection in heavy oil edge and bottom water reservoir from three aspects of geology, water production law and technology. Than the judgment matrix is established. There is little interference from human factors in the process of well selection, and the rationality of the method has been verified by the effect of field actual well measures. This method is helpful to improve the well selection method system of CO_2 huff and puff in this kind of reservoir, and is a reasonable supplement to the existing well selection method which takes the oil increment as the only evaluation index.

1 Introduction

Heavy oil reservoir with edge and bottom water has the characteristics of high oil-water viscosity ratio and low water displacement efficiency[1]. In the process of long-term depressurization production, the invasion of water leads to the rapid rise of oil well water cut, and the recovery ratio of the reservoir is poor[2-4]. A large number of studies and field practice show that CO_2 huff and puff can not only reduce viscosity and supplement formation energy, but also control water and increase oil production in heavy oil reservoirs. It is an effective measure to improve the recovery of heavy oil reservoir with edge and bottom water[5-7]. Optimizing measure wells through scientific well selection method of CO_2 huff and puff is the premise to ensure the effect of CO_2 huff and puff measures.

In recent years, experts have carried out a lot of research on CO_2 huff and puff and put forward a variety of well selection methods and principles: in 2003, Zhao Junsheng and others[8] put forward qualitative well selection conditions in terms of reservoir structure, reservoir characteristics, crude oil characteristics and construction technology through the analysis of 12 CO_2 huff and puff test wells in low-permeability reservoir; In 2009, Wang Xiande and others[9] summarized the examples of CO_2 single well huff and puff at home and abroad, according to the mechanism of CO_2 oil increase, combined with the characteristics of reservoir, crude oil and reservoir rock, they summarized and quantified the well selection criteria by using cluster analysis method; in 2013, Bi Yongbin and others[10] collected the evaluation factors of CO_2 huff and puff construction in Nanpu oilfield, they used the statistical principle to calculate the possibility of successful huff and puff when the value of a single factor changed, and applied the fuzzy evaluation method to establish an evaluation method suitable for huff and puff well selection potential of horizontal wells in complex fault blocks; in 2019, Jin Chunyu and others[11] established a set of quantitative well selection methods for CO_2 huff and puff in heavy oil reservoirs with edge and bottom water using the fuzzy comprehensive evaluation method based on the oil increase index after measures. To sum up, the quantitative well selection method for CO_2 huff and puff in heavy oil reservoir with edge and bottom water has been proposed, however, the oil increment is the only evaluation index of these methods. In fact, although some CO_2 huff and puff wells can not achieve significant oil increase, they can effectively inhibit water production, which also reflects the effective mitigation of interlayer contradictions. Therefore, the "water content" index is indispensable for the accurate characterization of the effect of CO_2 huff and puff measures.

Based on this, a new quantitative well selection method of CO_2 huff and puff in heavy oil reservoir with edge and bottom water is established. The method is based

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on fuzzy comprehensive evaluation theory[12] and analytic hierarchy process, and takes the water cut after CO_2 huff and puff as the evaluation index. We have designed 175 typical models to screen the sensitive factors and laws of CO_2 huff and puff well selection in heavy oil reservoir with edge and bottom water from three aspects: reservoir geological conditions, water production law and construction technology. We establish the judgment matrix according to the obtained factors and laws The scientific well selection process of this method can reduce the interference of human factors and meet the needs of quantitative characterization of multi factor well selection. The rationality of the method is verified by the effect of field practical measure wells. Moreover, this method is helpful to improve the well selection method system of CO_2 huff and puff in this kind of reservoir. It is a reasonable supplement to the existing well selection method which takes the oil increment as the only evaluation index.

2 well selection method

2.1 Establishment process

The method is based on fuzzy comprehensive evaluation theory and analytic hierarchy process. Since the water cut after CO_2 huff and puff has a good correlation with the final oil increment, the water cut after CO_2 huff and puff is taken as the evaluation object.

The first step: determination of factor set and evaluation set

Firstly, a set of n factors that affect the water cut after CO_2 huff and puff is established, which is called factor set.

$$U=\left(u_1,u_2,\cdots,u_n\right) \tag{1}$$

In this method, 18 sensitive factors (n = 18) obtained from 175 typical models of heavy oil reservoir in three rounds of CO_2 huff and puff are taken as target factors. These sensitive factors have different degrees of influence on the water cut after CO_2 huff and puff.

Then, the evaluation set is determined according to the influence of various factors on the water cut after CO_2 huff and puff.

$$V=\left(v_1,v_2,\cdots,v_m\right) \tag{2}$$

The second step: single factor evaluation

The single factor evaluation of water cut after CO_2 huff and puff is carried out by using the single ranking method for continuous variables. The established factor set and evaluation set are evaluation tools.

The third step: determination of initial weight vector

According to the influence degree of each sensitive factor on water cut after CO_2 huff and puff, the weight of each factor is calculated by AHP. Then, the weight set is established, which is expressed as weight vecto.

$$\mathop{A}\limits_{\circ}=(a_1,a_2,\cdots,a_n) \tag{3}$$

In this formula, a_i is the weighted value of the i-th factor. general provisions:

$$\sum_{i=1}^{n}a_i=1 \tag{4}$$

The fourth step: comprehensive evaluation calculation

The single factor fuzzy evaluation of the i-th factor is a fuzzy subset of Evaluation set V:

$$\mathop{R}\limits_{\circ}{}_i=(r_{i1},r_{i2},\cdots,r_{im}) \tag{5}$$

Then the evaluation matrix on Evaluation set V is:

$$\tilde{R}=\begin{bmatrix} r_{11} & r_{12} & \text{K} & r_{1m} \\ r_{21} & r_{22} & \text{K} & r_{2m} \\ \text{M} & \text{M} & \Lambda & \text{M} \\ r_{n1} & r_{n2} & \Lambda & r_{nm} \end{bmatrix} \tag{6}$$

So the fuzzy comprehensive evaluation subset $\mathop{B}\limits_{\circ}$ for the evaluation object is a fuzzy subset on Evaluation set V:

$$\mathop{B}\limits_{\circ}=\mathop{A}\limits_{\circ}\otimes\mathop{R}\limits_{\circ} \tag{7}$$

In the fuzzy transformation, $\mathop{A}\limits_{\circ}$ is the fuzzy subset (weight vector) on U, $\tilde{R}$ is the evaluation matrix, then $\mathop{B}\limits_{\circ}$ is the evaluation result matrix of the evaluation object. For $\mathop{B}\limits_{\circ}=\left(b_1,b_2,\cdots,b_m\right)$, in practical application, the multiplication of $\mathop{A}\limits_{\circ}$ and $\mathop{B}\limits_{\circ}$ is usually performed:

$$b_j=\sum_{i=1}^{n}a_i\times r_{ij},\quad i=1,2,\text{L}\ ,n;\ j=1,2,\text{L}\ ,m \tag{8}$$

In the formula above, b_j is the evaluation result of the j-th evaluation object (It is the decision factor corresponding to the well selection method).

The fifth step: correction and adjustment of well selection method

The decision factors corresponding to 525 wells-times (175 wells × three rounds of huff and puff) of typical models are obtained by comprehensive evaluation and calculation. After ranking the decision factors in descending order, the correlation between the ranking and the water cut after CO_2 huff and puff in the typical model is tested. Adjust the initial weight vector and repeat the third, fourth and fifth steps to modify and adjust the well selection method. When the ranking of decision factors is well positively correlated with the water cut after CO_2 huff and puff (that is to say, the smaller the sort number, the lower the water cut after huff and puff), the final weight vector is determined.

2.2 Determination of factor set and evaluation set

According to 175 typical models of heavy oil reservoir, 18 sensitive factors were selected to establish target factor set (Table 1). These sensitive factors have different degrees of influence on the water cut after CO_2 huff and puff. Take the first round of CO_2 huff and puff data as an example: the larger the difference and ratio between the maximum and minimum water cut after huff and puff, the more sensitive the factor is.

To determine the evaluation set, it is necessary to determine the corresponding values or ranges of the 18 influencing factors. For non-continuous variable factors, the conventional factor level is directly used to determine the factor value. Taking the dip angle as an example: three conventional values 3°、6°、10° were used as factors value. For continuous variable factors, it is necessary to determine the value range of factors according to the conventional value range. Taking the pay-zone thickness as an example: the conventional value range of 0m ~ 14m is taken as the factor value interval.

Table 1. List of well selection factors.

Factors	Sensibility / first round	Sensitivity law	Difference between maximum and minimum water cut / first round	Ratio of maximum to minimum water cut / first round
Stratigraphic dip /°	Relatively weak	Positive correlation	0.002	1.05
Location of interlayer	Relatively weak	It's the highest in the middle	0.020	1.87
pay-zone thickness /m	Relatively strong	Positive correlation	0.047	11.74
Sedimentary rhythm	Relatively strong	Anti rhythm is better	0.051	13.75
Heterogeneity（lorentz coefficient）	Strong	Positive correlation	0.192	Infinity
Water cut after commissioning /f	Relatively strong	Positive correlation	0.006	1.22
Length of water producing section	Relatively weak	Negative correlation	0.026	2.63
Location of water producing section	Relatively weak	Relatively weak	0.030	31.00
Heterogeneity degree of water producing section	Relatively weak	Negative correlation	0.025	1.93
Position of horizontal section	Relatively strong	The upper part of positive rhythm is good, the rule of anti prosody is opposite	0.054	55.00
Water cut before huff and puff /f	Relatively weak	Positive correlation	0.013	Infinity
cyclic steam injection volume /sm^3	Relatively strong	Negative correlation	0.052	3.30
Gas injection rate /sm^3/d	Relatively weak	Positive correlation	0.009	1.40
soak time /d	Relatively weak	Negative correlation	0.029	2.75
Liquid recovery rate after well opening/rm^3/d	Strong	Positive correlation	0.242	10.44
Distance between parallel wells /m	Strong	Negative correlation	0.734	26.75
Liquid production of parallel wells /rm^3/d	Strong	Positive correlation	0.867	31.42
Turn of huff and puff	Strong	Negative correlation	0.292	6.31

For a certain factor, according to the definite factor value range, the influence law of all factors on water cut after huff and puff is compared. Here, the value range of 1 ~ 9 is used to assign values to different factors. The lower the water cut after huff and puff, the larger the value of the evaluation parameter (Table 2).

Table 2. Parameter value of evaluation set

Parameter value	Meaning
1	The numerical value of this factor makes the water cut reach the highest level after huff and puff
…	The numerical value of this factor makes the water cut reach the middle value after huff and puff
9	The numerical value of this factor makes the water cut reach the lowest level after huff and puff

Table 3. Evaluation of stratigraphic dip factors.

Stratigraphic dip /°	Water cut in the first round of well opening	score	Water cut in the second round of well opening	score	Water cut in the third round of well opening	score
3	0.030	9	0.158	9	0.261	9
6	0.030	6	0.182	5	0.269	7
10	0.032	1	0.204	1	0.290	1

2.3 Single factor evaluation

For discontinuous variables, the values of each factor can be directly assigned according to the correlation between the value of the factor and the water cut after huff and puff. Taking the stratigraphic dip as an example, it has three levels: 3°、6°、10°. According to the conclusion of typical model, the value of this factor is positively correlated with the water cut after huff and puff. The assignment is shown in Table 3.

For continuous variables, it will lead to the inconsistency of the judgment matrix if the judgment matrix is established based on subjective experience. Here, a single sort method for continuous variables is established. For a certain factor, according to the correlation law between the value of the factor and the water cut of the well after huff and puff, the inflection point and extreme point values are assigned and then fitted by sections. In this way, the correlation formula between the factor value and the evaluation parameter value is obtained. The evaluation parameters of any other factor values are calculated by the correlation formula. Taking cyclic steam injection volume as an example, the overall assignment rule is shown in Figure 1.

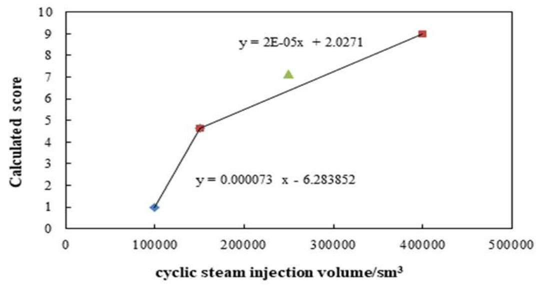

Figure 1. Regular chart of cyclic steam injection volume and Calculated score.

2.4 Determination of initial weight vector

According to the influence degree of each sensitive factor on water cut after CO_2 huff and puff, the weight of each factor is calculated by AHP. In this paper, the difference between the maximum and minimum water cut after huff and puff corresponding to different parameter values of each factor is used to characterize the influence of each sensitive factor on the water cut after CO_2 huff and puff. The initial weight of each sensitive factor is obtained by normalizing the difference between the maximum and minimum water cut after huff and puff (Table 4).

Table 4. Initial weight table.

Factors	Initial weight
Stratigraphic dip /º	0.00074
Location of interlayer	0.00743
pay-zone thickness /m	0.01747
Sedimentary rhythm	0.01895
Heterogeneity（lorentz coefficient）	0.07135
Water cut after commissioning /f	0.00223
Length of water producing section	0.00966
Location of water producing section	0.01115
Heterogeneity degree of water producing section	0.00929
Position of horizontal section	0.02007
Water cut before huff and puff /f	0.00483
cyclic steam injection volume /sm^3	0.01932
Gas injection rate /sm^3/d	0.00334
soak time /d	0.01078
Liquid recovery rate after well opening/rm^3/d	0.08993
Distance between parallel wells /m	0.27276
Liquid production of parallel wells /rm^3/d	0.32219
Turn of huff and puff	0.10851

2.5 Correction and adjustment of well selection method

For each factor, the decision factors corresponding to 525 wells-times (175 wells × three rounds of huff and puff) in the typical model are obtained by using the evaluation matrix. After ranking the corresponding decision factors of 525 wells-times in descending order, the correlation between the ranking and the water cut after CO_2 huff and puff in typical model is tested. Adjust the initial weight vector and repeat steps three, four and five to modify and adjust the well selection method. Until the ranking of decision factors has a good positive correlation with water cut after CO_2 huff and puff (Figure 2). At this point, the lower the score of the well, the higher the water cut after CO_2 huff and puff, reflecting the worse the effect of measures (Figure 3).

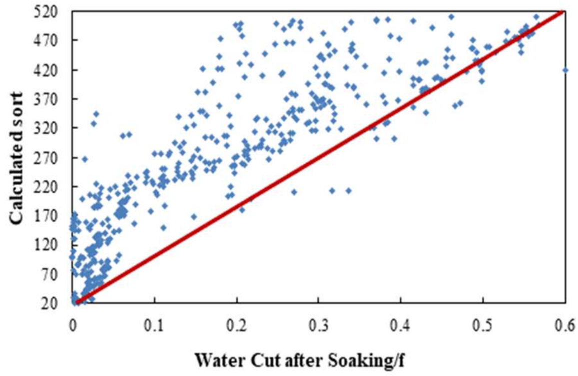

Figure 2. Correlation between water cut after soaking and decision factor ranking of 525 well-times in typical model after huff and puff

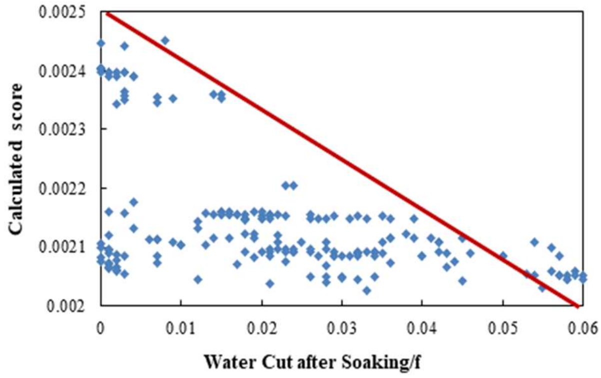

Figure 3. Correlation between water cut and theoretical score of 525 well-times in typical model

At this time, the determined weight vector is the final weight vector, as shown in the Table 5.

Table 5. Final weight of factors.

Factors	Final weight
Stratigraphic dip /º	0.00282
Location of interlayer	0.0169
pay-zone thickness /m	0.08263
Sedimentary rhythm	0.0169
Heterogeneity（lorentz coefficient）	0.0939
Water cut after commissioning /f	0.01502
Length of water producing section	0.01972
Location of water producing section	0.02441
Heterogeneity degree of water producing section	0.01878
Position of horizontal section	0.02066
Water cut before huff and puff /f	0.03099
cyclic steam injection volume /sm^3	0.07042
Gas injection rate /sm^3/d	0.01315
soak time /d	0.0385
Liquid recovery rate after well opening/rm^3/d	0.14178
Distance between parallel wells /m	0.14178
Liquid production of parallel wells /rm^3/d	0.15775
Turn of huff and puff	0.0939

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3 Field application of well selection method

Taking 37 horizontal wells of multi round CO_2 huff and puff in A oilfield as an example. The well selection method was applied to evaluate the 37 wells. The final sorting results are shown in the Table 6.

The correlation between water cut and well selection decision factors of 37 wells after multiple rounds of CO_2 huff and puff is shown in Figure 4. The correlation between water cut and well selection decision factor ranking of 37 wells after multiple rounds of CO_2 huff and puff is shown in Figure 5.

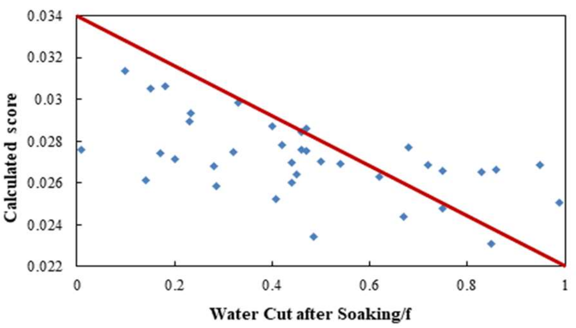

Figure 4. Correlation between water cut and theoretical score of actual wells after multiple cycles of huff and puff

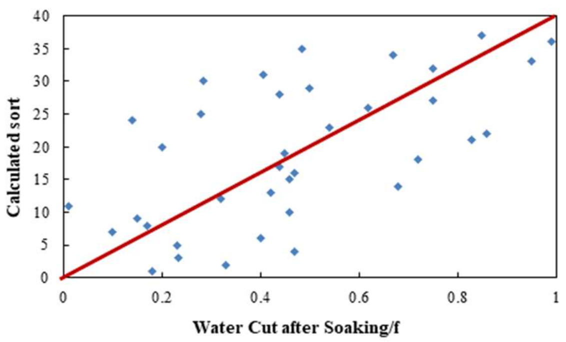

Figure 5. Correlation between water cut and calculation sort of actual wells after multiple cycles of huff and puff

Table 6. Well selection results of actual horizontal wells for multiple rounds of CO_2 huff and puff

Well Name	Water cut after huff and puff /f	Calculation score	Actual sort	Calculation sort
1stG120-P1CP1	0.01	0.0276006	1	12
1stG104-5P125	0.1	0.0313372	2	1
2ndG104-5P105	0.14	0.0261232	3	29
1stG104-5P106CP1	0.15	0.030537	4	3
1stG104-5P105	0.17	0.0274394	5	16
1stG104-5P78CP1	0.18	0.0306097	6	2
1stG104-5P115	0.2	0.0271678	7	17
1stG24-P4	0.23	0.0289228	8	6
1stG24-P2	0.233	0.0293259	9	5
1stG104-5P10	0.28	0.0267854	10	23
1stG104-5P13	0.285	0.0258526	11	31
1stG104-5P28	0.32	0.0274509	12	15
1stG104-5P44	0.33	0.0298705	13	4
1stG104-5P112	0.4	0.0287163	14	7
1stG106-5CP1	0.407	0.0252184	15	32
1stG104-5P100	0.42	0.0278219	16	10
1stG24-P3	0.44	0.0269984	17	19
1stG104-5P97	0.44	0.0260188	18	30
1stG104-5P117	0.45	0.0264135	19	27
1stG104-5P93	0.46	0.0284233	20	9
1stG104-5P91CP1	0.46	0.02758	21	13
1stG104-5P1	0.47	0.0286056	22	8
1stG104-5P79	0.47	0.0275332	23	14
2ndG104-5P115	0.484	0.0234217	24	36
1stG104-5P101	0.5	0.0270513	25	18
1stG24-P1	0.54	0.026902	26	20
1stG104-5P32	0.62	0.026285	27	28
1stG104-5P102	0.67	0.024408	28	35
1stG104-5P12	0.68	0.0277	29	11
1stG104-5P34	0.72	0.0268442	30	22
1stG104-5P82	0.75	0.0265636	31	25
1stG104-5P96	0.75	0.0247866	32	34
1stG104-5P85	0.83	0.0265052	33	26
2ndG104-5P97	0.85	0.023106	34	37
1stG104-5P21	0.86	0.0266206	35	24
3rdG104-5P97	0.95	0.0268761	36	21
3rdG104-5P115	0.99	0.0250627	37	33

According to the comparison between the evaluation results of well selection and the actual data: there is an obvious inverse correlation between water cut and well selection decision factors in 37 wells after multiple rounds of CO_2 huff and puff; There is a positive correlation between the water cut and the order of well selection decision factors in 37 wells after multi round CO_2 huff and puff. It is proved that the well selection method can optimize the target well based on the water cut after huff and puff.

4 Conclusions

(1) A new quantitative well selection method of CO_2 huff and puff in heavy oil reservoir with edge and bottom water is established. The method is based on fuzzy comprehensive evaluation theory and AHP, and takes the water cut after CO_2 huff and puff as the evaluation index. According to the sensitive factors and their influence rules obtained from 175 typical models of heavy oil during three rounds of CO_2 huff and puff, the judgment matrix is established. This method is helpful to improve the well

selection method system of CO_2 huff and puff in this kind of reservoir. It is a reasonable supplement to the existing well selection method which takes the oil increment as the only evaluation index.

(2)Two efforts have been made to improve the accuracy and applicability of the judgment matrix of the method: a set of single ranking method for continuous variables in evaluation factors is established to solve the problem of inconsistent judgment matrix of continuous variables; The 525 well-times production data in typical model is used to verify and adjust the weight of well selection factors, so that the well selection factor ranking has a good positive correlation with water cut after CO_2 huff and puff.

(3) The well selection method is used to evaluate the well selection of 37 horizontal wells in A oilfield, which is a typical heavy oil reservoir with edge and bottom water. By comparing the evaluation results of well selection with the actual production data, it can be seen that: the water cut of 37 wells after multiple rounds of CO_2 huff and puff has obvious inverse correlation with the well selection decision factors, while the well selection sequence has good positive correlation with the water cut after huff and puff, which indicates that the better the well selection sequence is, the better the measure effect will be. It also proves that the well selection method can optimize the target well based on the water cut after huff and puff.

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