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Fuzzy comprehensive evaluation of the suitability of downhole inflow control device in sandstone reservoir

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Abstract

The downhole inflow control device (ICD) could control the production profile of every section in horizontal well and the edge and bottom water coning, so it is important in enhancing oil and gas recovery. To quantitatively depict ICD's suitability in horizontal wells requires analyzing reservoir parameters like permeability variation coefficient, average permeability, the ratio of vertical permeability to horizontal permeability and the technology parameters like tube string size, horizontal section length, segment number and the pressure loss ratio between ICD and reservoir. With fuzzy mathematical method, this work has analyzed these factors through relative subordinate function and established the fuzzy comprehensive evaluation model to study the suitability of ICD in sandstone reservoirs by the weight of each factor and fuzzy relationship matrix. The fuzzy evaluation and simulation results prove this method could well evaluate the suitability of ICD in sandstone reservoirs and it is significant for the application of ICD in horizontal well development.

Keywords: fuzzy comprehensive evaluation, inflow control device, sandstone reservoir, subordinate function

1. Introduction

As a new technique, the intelligent completion system is basic for intelligent oil field establishment. With its application, the downhole inflow control device (ICD) also becomes more prevalent. ICD in horizontal

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wells can effectively slow down the water cone and gas cone, increase the sweep area of gas drive or water drive, promote single well productivity and then enhance oil recovery. The choke flow of ICD can control the flow in the downhole production layer and adjust the production profile to get the balancing development and optimized production of oil and gas. But many elements would affect the horizontal well productivity with ICD and to describe, analyze and evaluate them is hard because of their vagueness and uncertainty. Therefore this work introduces the fuzzy mathematical method, an evaluating method with theory of fuzzy set which integrates evaluating matrix and the objective fuzzy matrix. It could tell the quality of many factors objectively and make quantitative evaluation correctly. The key point in establishing optimized evaluation model with fuzzy mathematics is in determining the evaluating index factor, index weight, and subordinate function matrix affecting the suitability of ICD and then establishing the fuzzy comprehensive evaluation model.

Nomenclature

ΔP_{ICD}	pressure loss of flow passing ICD [MPa].
$\Delta P_{reservoir}$	pressure loss of flow passing reservoir [MPa].
K_h	horizontal permeability of reservoir [$10^{-3}\mu m^2$].
K_v	vertical permeability of reservoir [$10^{-3}\mu m^2$].
r_{ij}	fitness of the evaluation parameter with respect to the optimal value [dimensionless].
R	single factor fuzzy evaluation matrix.
R_1	first level single factor evaluation matrix.
$R_1^{reservoir}$	first level evaluation matrix about reservoir parameters.
$R_1^{technology}$	first level evaluation matrix about technology parameters.
X_{ij}	the evaluation parameter number j in case i.
X_{oj}	the correspondent parameter of the best suitability.
X_{wj}	the correspondent parameter of the worst suitability.
U	factor set.
V	comprehensive evaluation matrix.
V_1	the first level comprehensive evaluation matrix.
V_2	the second level comprehensive evaluation matrix.
w_i	weight of single factor.
W	weight matrix.
W_1	the first level weight matrix.

2. Univariate analysis

ICD limits the production of high permeability zone and balance the horizontal section inflow profile by generating an additional resistance between reservoir and pipe. The dominating factors influencing the suitability of ICD can be summarized as in two parts: (1) the inflow part relating to reservoir properties, including reservoir heterogeneity, permeability, reservoir thickness and K_v/K_h; (2) the outflow part mainly relating to technology like tube string size, segment number, horizontal section length and $\Delta P_{ICD}/\Delta P_{reservoir}$ (Birchenko et al., 2008).

Further analyses (Shuai, 2012) indicate that:

- The technological factors influencing ICD completion meet the following order, segment number >$\Delta P_{ICD}/\Delta P_{reservoir}$ > horizontal section length >tube string diameter. The first two factors can significantly influence the experiment result while the latter two's influences are relatively small.
- The reservoir factors influencing ICD completion meet the following order, variation coefficient > average permeability > reservoir thickness > K_v/K_h . Also the first two factors can greatly influence the experiment and the latter two's influences are small. Given the poor water control effect in thin layer bottom water reservoir, the thickness is not included in comprehensive evaluation.

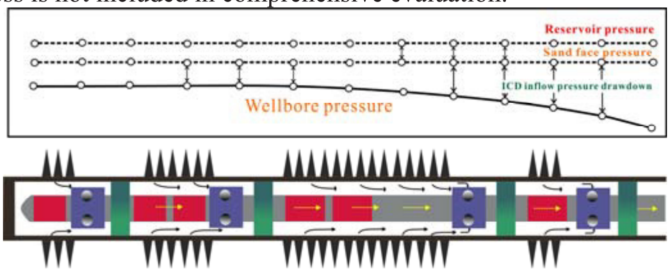

Fig1 Description of mechanism in ICD choke flow

3. Fuzzy comprehensive evaluation model

3.1. Establishing factors set

The factors are classified as follows: U= {reservoir parameters, technology parameters} is used as the second level of ICD completion suitability factor set. Reservoir parameter U_1 = {permeability, permeability variation coeffient, K_v/K_h} and U_2 ={horizontal section length, tube string diameter, $\Delta P_{ICD}/\Delta P_{reservoir}$, segment number} are the first level factor set.

3.2. Establishing weight matrix of influencing factors

The affecting factors are of different significance. The single factor subordinate function determined by subordinate function could only reflect the suitability of single factor and is still univariant analysis (Fang et al, 2010). Therefore, to present the importance of different factors, certain weights w_i are given to them as follows:

$$W = \{w_1, w_2, w_3, w_4\} \tag{1}$$

The weight set must meet the requirement of normalization and non-negative.

$$\sum_{i=1}^{m} w_i = 1 \tag{2}$$

$$w_i \geq 0 \tag{3}$$

The analytic hierarchy process is used to determine the weight of first level parameters and subjective assignment method is used for the second level parameters.

3.3. Establishing evaluation set

The fuzzy comprehensive evaluation model for different cases of ICD completion is as follows:

$$V = R \times W = \{V_1, V_2, V_3 \cdots\} \tag{4}$$

where, W is the weight matrix, R is the single factor fuzzy evaluation matrix of each influencing factor and V is the comprehensive evaluation matrix of factors influencing ICD application.

3.4. Establishing subordinate function

The subordinate function of the factors is the basic for comprehensive evaluation of ICD completion suitability. For convenience, the function adopted here is relative subordinate function as follows:

$$r_{ij} = \left| \frac{X_{ij} - X_{wj}}{X_{oj} - X_{wj}} \right| \tag{5}$$

where, X_{ij} is the evaluation parameter number j in case i, X_{oj} is the correspondent parameter of the best suitability, X_{wj} is the correspondent parameter of the worst suitability and r_{ij} is the fitness of the evaluation parameter with respect to the optimal value.

X_{oj} and X_{wj} are determined by univariant analysis of ICD completion suitability and the range of reservoir and technology parameters in China. The correspondent evaluation parameter r_{ij} can then be calculated by Equation (5).

The relative fitness r_{ij} varies from 0 to 1 when comprehensively evaluating ICD suitability with different cases. The larger value of r_{ij} means the higher suitability of ICD completion. The matrix of all r_{ij} values is the fuzzy comprehensive suitability matrix of ICD completion R(x).

3.5. Fuzzy evaluation

3.5.1. The importance order of different factors

According to the sensitive analysis of different influencing factors, we can give relative importance order for each factor as shown in Table 1.

Table 1 Importance order of different factors

scale	Importance
1	Equal importance of the two compared factors
2	Between 1 and 3
3	One is slightly more important than the other
4	Between 3 and 5
5	One is obviously more important than the other
6	Between 5 and 7
7	One is strongly important than the other

3.5.2. Establishing weight matrix of evaluation factors

- First level weight matrix

The weight values of reservoir and technology parameters are shown in Table 2 and 3 with reference to the above importance order.

Table 2 Weight of Reservoir parameters

	Variation coefficient	permeability	Kv/Kh
Variation coefficient	1	5	7
permeability	0.2	1	3
K_v/K_h	0.14	0.33	1

Table 3 Weight of technology parameters

	Segment number	Tube string diameter	Horizontal section length	$\Delta P_{ICD}/\Delta P_{reservoir}$
Segment number	1	5	4	3
Tube string diameter	0.2	1	0.5	0.33
Horizontal section length	0.25	2	1	0.5
$\Delta P_{ICD}/\Delta P_{reservoir}$	0.33	3	2	1

- Second level weight matrix

Technology parameters in ICD completion are usually artificially set according to reservoir parameters and production requirements. Since it is controlled by people, its impact on ICD suitability is relatively small. The weight of reservoir parameters and technology parameters is obtained through expert experience and it is $W_2=(0.65, 0.35)^T$.

4. Case Study

A horizontal well is planned to develop a sandstone heterogeneous reservoir and intelligent completion is conducted. ICD is installed to control the fluids flowing into the wellbore. The evaluation parameters of 6 cases are shown in Table 4.

Table 4 Evaluating parameters

Evaluating parameters		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Reservoir parameters	Variation coefficient(fraction)	0.4025	0.5471	0.1605	0.5026	0.1702	0.2531
	Average permeability($10^{-3}\mu m^2$)	432.9	196.59	490	1460	4390	527
	K_v/K_h (fraction)	0.25	0.3	0.5	0.1	0.2	0.4
Technology parameters	Segment number	3	4	7	6	6	5
	$\Delta P_{ICD}/\Delta P_{reservoir}$	0.8	1	0.9	1	0.8	1
	Horizontal length(m)	255	266	900	755	914	421
	Tube string diameter (mm)	124.26	121.4	114.3	152.4	157.48	139.7

The appropriate range of parameters is determined by reference to large amount of the actual parameters in different reservoirs and is shown in Table 5.

Table 5 Appropriate range of evaluating parameters in ICD completion

Evaluating parameters		Best value	Worst value
Reservoir parameters	Variation coefficient(fraction)	0.8	0.1
	Average permeability($10^{-3}\mu m^2$)	10000	150
	K_v/K_h (fraction)	0.5	0.08
Technology parameters	Segment number	10	1
	$\Delta P_{ICD}/\Delta P_{reservoir}$	1	0.1
	Horizontal length(m)	1000	200
	Tube string diameter (mm)	63.5	165.1

The fuzzy subordinate function for each plan is got with the evaluating parameters and subordinate function showed as Equation (5).

The fuzzy subordinate function of reservoir parameters $R_1^{Reservoir}$is

$$R_1^{reservoir} = \begin{bmatrix} 0.4322 & 0.0287 & 0.4048 \\ 0.6387 & 0.0047 & 0.5238 \\ 0.0864 & 0.0345 & 1.0000 \\ 0.5752 & 0.1331 & 0.0476 \\ 0.1003 & 0.4305 & 0.2857 \\ 0.2187 & 0.0327 & 0.7619 \end{bmatrix}$$

The fuzzy subordinate function of technology parameters $R_1^{technology}$ is

$$R_1^{\text{technology}} = \begin{bmatrix} 0.2222 & 0.4021 & 0.0423 & 0.7778 \\ 0.3333 & 0.4301 & 0.0508 & 1.0000 \\ 0.6667 & 0.5000 & 0.5384 & 0.7222 \\ 0.5556 & 0.1250 & 0.4269 & 0.6667 \\ 0.5556 & 0.0750 & 0.5492 & 0.6111 \\ 0.4444 & 0.2500 & 0.1700 & 1.0000 \end{bmatrix}$$

4.1. First level evaluation result

The comprehensive evaluation result is calculated with the fuzzy comprehensive model. The comprehensive evaluation matrix of reservoir factors on ICD completion suitability is:

$$V_1^{\text{reservoir}} = R_1^{\text{reservoir}} \times W_1^{\text{reservoir}} = (0.3540 \quad 0.5101 \quad 0.1501 \quad 0.4496 \quad 0.1773 \quad 0.2272)^T$$

And comprehensive evaluation matrix of technology factors is:

$$V_1^{\text{technology}} = R_1^{\text{technology}} \times W_1^{\text{technology}} = (0.3413 \quad 0.4571 \quad 0.6480 \quad 0.5276 \quad 0.5274 \quad 0.5192)^T$$

Therefore, the first level comprehensive evaluation matrix of the 6 cases ICD suitability is :

$$V_1^{\text{comprehensive}} = \begin{bmatrix} 0.3540 & 0.5101 & 0.1501 & 0.4496 & 0.1773 & 0.2272 \\ 0.3413 & 0.4571 & 0.6480 & 0.5276 & 0.5274 & 0.5192 \end{bmatrix}^T$$

4.2. Second level evaluation result

Multiply the first level comprehensive evaluation matrix by the second level weight matrix and we get the second level comprehensive evaluation matrix:

$$V_2^{\text{comprehensive}} = V_1^{\text{comprehensive}} \times W_2 = (0.3496 \quad 0.4915 \quad 0.3244 \quad 0.4769 \quad 0.2998 \quad 0.3294)$$

The result suggests that case 2 is the best while case 3 is the worst just from the aspect of reservoir factors. The main reason is that case 2 has the largest variation coefficient, so the inflow profile is most unbalanced and the probability of water coning is the highest. In this case, ICD completion could display its best water control effect and is most suitable. From the aspect of technology, case 3 is the best while case 1 is the worst, because case 3 has the largest segment number. Combining the 2 factors together, we find case 2 is the best while case 5 is the worst.

5. Conclusions

- The univariate analysis of influence of the reservoir and wellbore parameters on the suitability of ICD could only get qualitative result. It could not reflect the interaction among various factors and is not appropriate to evaluate the suitability in real oil reservoirs.

- Fuzzy mathematical comprehensive evaluation quantifies the interactions among the factors to get quantitative result. This is helpful in evaluating the suitability of ICD and choosing the development options in real oil reservoirs.
- However, the limitation of this work might lie in the inadequate consideration of the interaction among those factors since the analyses here are based on the site conditions. The subordinate functions for each factor are determined when only considering the single factor. Therefore, the method might need further improvement in real applications.

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