Analysis Method for Tracer Production Curve in Fractured-vuggy Reservoir

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Abstract: The fracture-vuggy carbonate reservoir in Tahe oilfield is unique and difficult to be analyzed by conventional tracer analysis technology. Based on the geological characteristics of fracture and vug in reservoirs, a theoretical model is established by applying fluent to simulate the flow characteristics of fluids in fracture-vug, so as to analyze the characteristics of tracers under different conditions: The output of tracer under the condition of single fracture shows kurtosis, while under the condition of single vug without kurtosis; The combination of many fractures can either enhance the peak height or show multiple peaks, while the combination of multiple vugs still shows no kurtosis but only extends the range; The output characteristics of series combination of fracture/vug were more influenced by themselves. The smaller the volume of vug is, the less the fractures were influenced, and thus the production becomes more and more similar to fractures; while the rest of them show vug characteristics. Through applying the tracer production curve analysis theory to the actual production data of the field tracer test, and establishing the fracture tunnel ratio and the dominant channel direction judgement method to characterize the reservoir flow path, we found that the ratio of the fracture and vug in the target area is 1:9; the direction of the dominant channel is determined by the size of the Interdistance intercepting area of the injection production well - the larger the section area is, the better the channel is. It indicates that the analytical method of tracer production curve in fracture-vug reservoir is applicable, and it can lay a foundation for improving the theory of tracer production characteristics analysis in fracture-vug reservoirs.

1. Introduction
Tahe oilfield is located in northern Tarim Basin. The Ordovician carbonate reservoir is the largest carbonate fractured reservoir found in China [1, 2]. Because the reservoir has undergone many tectonic movements and has suffered severe weathering, denudation and leaching [3, 4], the formation of fracture-vuggy reservoir, which is composed of vugs, cracks and dissolve holes, is extremely irregular and distributes randomly [5-7]. The vug is the most important storage space, and the crack is not only the main storage space, but also the main connecting channel [8-10]. The complicated combination of fracture and vug leads to various flow states of internal fluids, and most of the fluid flow does not conform to the Darcy seepage rule. This has caused great trouble for water injection
production and development.

Water flooding has become the most important developmental way of stabilizing production and improving recovery of fracture-cavity reservoir in Tahe oilfield, but the water flooding injection water can easily break through the formation of dominant channel, thus rapidly resulting in single effect of water flooding of injection wells group; because of the limited scope of water wave, the effect of water injection gradually becomes poor, which is not conducive to the development of oil production [11]. Because the reservoir flow is unclear, conventional construction technology and methods cannot meet the current demand of adjusting flow [12]. In order to effectively recognize the characteristics of reservoir flow channel, tracers are commonly used for tracing research, while at present, the effective analysis of tracer data is only established and applied in sandstone reservoir system [13]. Due to the complex fracture vug structure of carbonate fractured-vuggy reservoir, sandstone reservoir analysis method cannot be effectively applied in fractured-vuggy reservoir. Even if tracing research can be carried out through tracer, the output curve is too complicated to be effectively analyzed, and thus it cannot guide the following research [14].

Therefore, based on the characteristics of fractured-vuggy reservoir and tracer action principle, the theoretical analysis of the influence of fracture-vuggy reservoir characteristics on tracer production characteristics was carried out, combined with the actual tracer curve for analysis and interpretation, and it was supported by field data.

2. Design of the conceptual model of fracture-vug and the study of the flow pattern of tracer

2.1. Conceptual model of fracture-vug

Therefore, a conceptual mathematical model of fracture-vug can be established, as shown in Fig.1:

![Fig.1 Conceptual model of fracture-vug](image)

The result of identifying the fracture form of the unit core imaging showed that the average width of the fracture was 2.2mm, and that the height of the fracture ranged from 0.6m to 1.0m. Then the size of the conceptual model can be set as follows: the height of the fracture was 0.9m, the width of the fracture was 2.2mm, and the length of the fracture was 50m. Through the analysis of vug, it was known that there were 9 vugs in the height of 0~2m, accounting for 18% of the total number of vugs; 5 vugs in the height of 2m~4m, accounting for 10%; 36 vugs were higher than 4m, accounting for 72% of the total, and the average height of the vug was 7.7m. Because the geometrical shapes of vug were extremely irregular and the majority of vugs were unfilled and partial filled ones, the conceptual model can thus be established as follows: a cube model with 5m of the side length, without internal filling, can reflect the effects of irregular vug on fluid.

2.2. The motion characteristics of the fluid in the model

The unique vug structure of fracture-vuggy reservoir caused the fluid flow to differ from the linear seepage in sandstone reservoir development process. The large and irregular space of flow volume had large effects on the flow pattern, especially on the diffusion / dispersion of tracer, and thus the output characteristics can be influenced. Therefore, to recognize the flow state of the tracer in the fracture-vug reservoir was helpful for the characterization and interpretation of the characteristics of
the output curve.

2.2.1. Simulation parameter design
(1) Modeling and meshing: we used the workshop-Design Modeler in fluent software to establish the conceptual model of fracture and vug according to the conceptual model, and divide meshed by Mesh.
(2) The definition of physical property: ①The outer boundary of the fractures and vugs were a rock layer that was not permeable (the carbonate matrix did not have the significance of reservoir permeability); ②The target medium of the injected fluid was the formation water of the target reservoir, with the density of 1.14kg/m³ and the viscosity of 1mPa·s; ③The boundary conditions at both ends: the entrance was a constant velocity (0.25m/s), the exit was a constant pressure (atmospheric pressure 0.1MPa).

2.2.2. Simulation results analysis
The velocity streamline distribution in the fluid in the vug model was shown in Fig.2:

As can be seen from Fig.2, the fluid at a certain velocity showed a distinct difference in the fracture and the vug: 1) in the fractures at both ends of the cave, the fluid only presented a good linear flow in the horizontal direction, and only the flow rate changed when the fluid passed through the cave. The flow velocity in the inlet section was faster than that at the outlet end; 2) the streamline of the fluid which got into the vug through fractures is in disorder (a velocity of different positions, different linear perturbations, indicating that the injected tracer), after entering the vug will be subject to strong interference, increasing the tracer dilution and diffusion, and there was no law to tracer production in the vug (not available sandstone tracer production rules). Therefore, it was necessary to analyze the tracer output characteristics of the fracture-vuggy reservoir.

3. Theoretical analysis of the output characteristics of tracer in fracture-vuggy

3.1. Effect of single fracture (vug) on the output characteristics of tracer
For the conventional tracer output curve, the two main characteristic parameters were the output concentration and time: 1) the output concentration of tracer was affected by flow space and dilution / diffusion, the greater the influence, the lower the concentration of the output liquid; 2) the breakthrough time of the tracer was influenced by the size of the space, the smaller the volume of the flow, the shorter the breakthrough time. Based on the characteristics of the conventional tracer output curve, single fracture and single vug models were used to analyze the characteristic curves of tracer output respectively.

First, assuming that the tracer injection slug was not diluted/ diffused, then the injected slug in wells can be continuously and overall recovered. Because the volume of vug was far greater than that of fracture, the output concentration of vug was relatively low, and the response time relatively delayed. Figure 3 (left) shows the curve characteristic.
Fig. 3 Effect of dilution / diffusion on the output of tracer (left without consideration, right with consideration)

The dilution / diffusion condition of the tracer was only the ideal hypothesis, and its dilution / diffusion phenomenon was inevitable. On account of the characteristics of dilution / diffusion, the tracer output won't be linear. In theory, the output state for single fracture should be present as in Fig.3: for single fracture, the fracture section that tracer flows was small, the dilution / diffusion degree of limited tracer in single fracture was limited, the breakthrough showed the normal distribution - the peak shape (fracture); however, for a single vug, the vug of large volume increased the irregular movement of tracer, with large degree of dispersion, in the collection and production process at the bottom of the well, the dilution was obvious, it was difficult to form a clear single slit arrow, but to appear as dynamic wave (vug-2) or flat surface (vug-1). Therefore, under a single fracture/cave condition, if tracer data show obvious single peak (peak is a relative concept), it can be understood as the characteristics of cracks; if a fluctuation / flat surface, the characteristics of vug.

3.2. Effects of multiple fractures (vugs) combination on the output characteristics of tracer

The fractures and vugs in the fractured-vuggy reservoirs were not single, most of which were combinations of various forms. The combination of fractures with fractures and vugs with vugs were discussed here. While fractures with fractures (vugs with vugs) in series were considered to be one crack (hole), so the case of parallel was discussed only.

(1) Effect of parallel fracture on tracer:

Fig. 4 Effect of crack combination on the output characteristics of tracer

First of all, take double fracture combination as an example. If the volume of the two channels were similar, the two channels’ tracer output appears overlap, leading to superposition of tracer concentration based on unit Nissan liquid, then a single fracture model should be formed as in Figure 4 (left), which showed a relatively high peak compared with single crack condition. If the two cracks’ channel volume was far apart, double peak model will appear. According to this kind of push, if multiple fractures were all close, it will eventually form a high single peak. If there were many fractures, it would be a multi peak form.

(2) The effect of the parallel vug on the tracer:
Fig. 5 Effect of cave combination on the output characteristics of tracer

Compared with the crack, no matter cave combination overlaps or not, it was difficult to form a relatively abrupt kurtosis (as in Fig. 5). This was because the tracer was too scattered in the vug, even if many vugs product tracer simultaneously, it was difficult to form a peak, as tracer was outputted from a large cave. Finally, the output curve can be wavy (left, blue dashed line) or flat (right, red dashed line). Compared with the volume of the vug, the volume of the fracture had much smaller effect on the tracer. Therefore, the peak of the tracer output curve was just a relative concept.

3.3. The effect of combination pattern on tracer

Simple fractures and vugs as well as their combinations have their own distinct effects on the concentration and time of tracer production characteristics, so the combination of fracture and vug should also have their own characteristic curves. The correlation analysis was as follows: (1) The features of tracer under the conditions of series fracture-vuggy mode: under the conditions of series fracture cave, no matter in the pattern of fracture-vuggy, vuggy-fracture, or fractures-vuggy-fracture (vuggy-fracture-vuggy) mode, after the tracer was injected into the vug, its flow pattern would be effected (seen in Fig. 2). The occurrence of strong dilution / diffusion in the vug leaded to difficulty in showing output characteristics of cracks, but showed the output characteristics of vug (seen in Fig. 5). (2) Tracer characteristics under the mode of parallel fracture-vuggy: the fractures showed the characteristics of fractures; the vug showed the output characteristics of the vug. As shown in Fig. 3 (right), the crack was relatively fast due to its small flow volume.

4. Analysis of the characteristics of the output curve of the tracer in the mine field

4.1. Construction situation

The injection and production well of the tracer monitoring well group: one injection well named TK860X; five production wells named TK-1, TK-2, TK-3, TK-4, TK-5

The invisible light tracing technique was selected as the tracer, which was an inert photoactive substance, not disturbed by the salinity of the mineral and other chemical substances; its detection limit was very low, and it can reach ppb level (1/1000 of the limit of chemical tracer detection); and it had high magnification, which can reflect the reservoir characteristics more accurately. However, there was also light intensity monitoring for formation water and injected water. It was necessary to determine background concentration (Tab. 1), which serves as a comparative data to determine whether the tracer was breaking through the surrounding well after the trace was injected.

| Injection well | Monitoring well | BY-1 (cd) | Average strength (cd) |
|----------------|----------------|----------|-----------------------|
| TK-1           | TK-2           | 86.7; 49.8; 76.5; 43.8; 84.5; 82.7; | 70.67       |
|                | TK-3           | 31.4; 32.2; 25.6; 33.4; 32.3; 33.2; | 31.35       |
|                | TK-4           | 42.7; 31.5; 28.3; 39.8; 41.7; 37.2; | 36.87       |

Tab. 1 Background strength of oil well output fluid in each unit
4.1.1. Injection determination method

In order to ensure the effective analysis and monitoring of tracers, the maximum dilution concentration of tracers should be determined, avoiding excessive dilution and inability to analyze and monitor. Seen in Formula (1):

\[ V_p = \pi R^2 \cdot \frac{H \cdot C \cdot \Phi \cdot N \cdot S_w \cdot a \cdot \lambda}{\lambda_p} \]  

(1)

In the formula: \( V_p \) - Maximum diluent volume, \( m^3 \); \( R \) - Average well spacing, \( m \); \( \phi \) - porosity, Value 0.30; \( S_w \) - water saturation, Value 0.55; \( a \) - Scavenging and efficiency, Value 0.35; \( C \) - Equal water absorption thickness coefficient, Value 0.30; \( N \) - Reservoir shape coefficient, Value 0.40; \( \lambda \) - Crack vug coefficient, Value 1.07.

According to the relevant basic data provided by the oil production plant, the maximum dilution volume of the tracer in the injection well group was calculated. See Tab.2:

| Well group | Reservoir shape coefficient | Average reservoir radius (m) | Average thickness of oil layer (m) | Equal water absorption thickness coefficient | Porosity of average oil layer | Water injection coefficient | Hole coefficient | Maximum diluent volume of tracer \( \times 10^4 m^3 \) |
|------------|----------------------------|------------------------------|-----------------------------------|-----------------------------------------------|-----------------------------|--------------------------|----------------|----------------------------------|
| TK-1       | 0.45                       | 1859.6                       | 57.99                             | 0.3                                           | 0.3                         | 0.55                     | 0.35           | 1.07                             | 518.6             |

Using the formula (2), the amount of the tracer can be obtained:

\[ A = s \cdot V_p \cdot \mu \]  

(2)

In the formula: \( A \) - Injection amount, kg; \( S \) - detection sensitivity, ppb\( (10^{-9}) \); \( \mu \) - Remainder coefficient (This was the 1.5 consideration of this new area).

By calculating, 7.80g industrial dry agent was needed. Through conversion and previous experiences in early construction, it was designed to be BY-1 water agent 22kg.

4.1.2. The injection parameters of tracer

According to the principle that injection pressure should be close to the injection pressure or slightly higher than the original injection pressure before putting the tracer, considering the parameters of the injection pump and the characteristics of tracer, we can optimize the injection parameters of the well group. Seen in Tab.3:

| Well group | Tracer species | Amount of tracer (kg) | Preparation concentration (%) | Construction pipe column | Injectio n mode | Tracer dosage (L) |
|------------|----------------|-----------------------|-------------------------------|--------------------------|----------------|------------------|
| TK-1       | BY-1           | 22                    | 100                           | The original column      | injection pressure | 22               |

4.2. Quantitative characterization of flow channels in fractured and vug reservoirs

4.2.1. Tracer output tracking data statistics

From the second day after injection, the first water sample of the target oil well was taken, and the sampling amount was about 500g (if the water cut was low, then the amount was added); During the first 10 days, two samples were sampled per day, and the tracer was encrypt in the oil well when the tracer was broken; 10 days later, when no tracer appeared, one sample was taken per day until the tracer appeared, and then changed to 2 samples a day; The time interval between two sampling times must be more than 8 hours; The oil sampling must be timely sent back to the laboratory, timely detected and analyzed by the person responsible for the record, decreasing sampling 1 /1 days, 1 /2, 1
times a day for 4 days...... Extend the sampling time until the notification of stop comes.

The sample of the TK-1 injection well had been sampled from the next day for 155 days, and the sample were sampled for 155 days; 692 samples were sampled and 526 were analyzed. Seen in Tab.4 in detail:

| Sampling well group | Sampling group | Sampling time | Sampling should be taken | Real sampling | Analytical sample | Sampling analysis rate | Remarks |
|---------------------|----------------|---------------|--------------------------|---------------|------------------|-----------------------|---------|
| TK-1                | TK-2           | 155           | 167                      | 164           | 159              | 97.0                  |         |
|                     | TK-3           | 155           | 147                      | 139           | 139              | 100.0                 |         |
|                     | TK-4           | 155           | 149                      | 140           | 135              | 96.4                  |         |
|                     | Tk-5           | 155           | 103                      | 94            | 93               | 98.9                  |         |
|                     | Total          | 721           | 692                      | 526           |                  | 76.0                  |         |

4.2.2. Analysis of tracer output curve

Before analyzing the actual tracer curve, we can identify potential characteristics based on the analysis of sandstone tracer characteristic curve and fracture vug tracer production characteristics: 1) the time range of tracer breakthrough point cannot effectively identify the channel type, only expressing the speed under the current channel, therefore, the channel type can be identified according to the subsequent output curve type; 2) the output strength of tracers only represents the fracture-vuggy type of the well spacing, the main channel was the crack dominated flow channel, and the rest were the flow channels dominated by the vug; 3) the channel time cost to see the tracer will be understood as the dominant channel, the channel without tracer cannot be calculated as dominant channel, the red line was the average background intensity of the well, the effective point and failure strength line point that were higher than the background intensity as well as the background package volume were the dominant channel volumes.

For example, Characteristics of tracer output curve in well TK-1:

![Fig.6 Tracer output curve of TK-1 well](image)

Through the analysis of the characteristics of the output liquid from Fig.6, there were two independent single fracture channels (or channels of cracks and cracks) in the interval between injection well TK-1 and production well TK-2, which were less affected by vug, and the peak value of light intensity was very high; compared with the two high peaks, the small peak fluctuating below the black dashed line can be judged as the volume of the vug, and the volume of the vug was not too large, which had little influence on the light intensity, and still it outputted 200 of the light intensity. In this curve, the breakthrough time of tracer was fast, followed by the characteristic curve of vug. Then the breakthrough time was the volume of vug, and the volume of vug developed in the whole interval.
4.3. Quantitative characterization of cracks and vug channels between wells

Through the analysis of the tracer curve, the volume surrounded by the effect point and the failure point was the dominant volume that characterizing the characteristics of the fractured reservoir.

(Dominant volume = time length range * Nissan amount)

First, the tracer curve was used to read the time range of crack and the time range of the vug. Then, the daily volume of the production was got and the dominant volume was calculated. Finally, the fracture/vug ratio was used to get the fracture/vug ratio to represent the characteristics of fracture-vuggy reservoirs.

The results were shown in Tab.5:

| well   | Time to characterize fractures, d | Time to characterize caves, d | Daily liquid-producing capacity, m³/d | Dominant volume, m³ | Fracture volume, m³ | Cave volume, m³ | fracture/cave ratio |
|--------|----------------------------------|--------------------------------|--------------------------------------|---------------------|-------------------|-----------------|-------------------|
| TK-2   | 11                               | 60                             | 20.7                                 | 1469.7              | 227.7             | 1242            | 0.1833            |
| TK-3   | 6                                | 97                             | 85.4                                 | 879.2               | 512.4             | 8223.8         | 0.0619            |
| TK-4   | 9                                | 91                             | 70.4                                 | 7040                | 633.6             | 6406.4         | 0.0989            |
| TK-5   | 12                               | 45                             | 70.4                                 | 1932.3              | 406.8             | 1525.5         | 0.2667            |
| All    | 38                               | 293                            | 210.4                                | 19238.2             | 1780.5            | 17457.7        | 0.1020            |

From Tab.5, it was known that the value of the fracture/vug ratio was the time range of the fracture or vug. The ratio of well (TK-2) with more obvious peak value were higher. Well (TK-5), because of less effective sampling of tracer, the time range of the vug was limited and the final vugs were higher. While well (TK-3) and well (TK-4), which were more fully sampled, the vugs were developed and the ratio was less than 0.1. The majority of the whole block was vug volume, accounting for about 91%, and the fracture accounted for about 9%.

Dividing the dominant channel volume (seen in Tab.5) and well spacing, we can get the flow cross-sectional area (average area wells linear range), seen in Tab.6:

| well   | Dominant total volume, m³ | well spacing, m | flow cross-sectional area, m² |
|--------|---------------------------|----------------|-----------------------------|
| TK-2   | 1469.7                    | 694            | 2.118                       |
| TK-3   | 8796.2                    | 1514           | 5.810                       |
| TK-4   | 7040                      | 2275           | 3.095                       |
| TK-5   | 1932.3                    | 2867           | 0.674                       |

The size can be understood as follows: fluid flow in fractured-vuggy reservoir was similar to the pipe flow, if in the process of diversing the charge tube and vice tube, the cross-sectional area of the size of two level pipeline directly affected the flow – the higher the cross-sectional area, the greater the dividing flow; similarly, when the circulation area was larger, the current direction of the channel was more dominant. And in the circulation area, the ratio will affect the flow rate to a certain extent, and the vug was more beneficial to the diversion.

Therefore, in the data characterization of tracer, the water well (TK-3) and well (TK-4) had the highest distribution, and well (TK-5) lower.

5. Conclusions

(1) According to the fractured core data of the mine, the concept of fracture/vug model established by FLUENT was used to simulate the flow state of fluid in the fracture cavity. It was found that the fluid in the fracture condition was linear flow, while the fluid flow in the cavity was irregular and the flow pattern was obvious.

(2) Through theoretical analysis, it was believed that the tracer output characteristics of single fracture was peak state, while single output characteristics was not obvious wave kurtosis; multi fracture combination will wither enhance the peak height or show multi peaks, and vug combination appeared without wave peaks but extended the range of influence; the output characteristics of fracture-vuggy combination was affected fully by the vug, showing no significant wave peak.

(3) Through tracing the field tracer experiment, using the theoretical method to analyze the output
characteristics of tracers, the volume ratio of fracture/vug was 1:9, which was equivalent to other fracture/vug data, indicating that the theoretical analysis was of practical significance.

(4) Combined with the injection production pattern in the well spacing and the advantages of channel injection wells volume, the calculated flow cross-sectional area serves as a way of mainstream channel analysis, the greater the cross-sectional area was, the greater the flow points were; in the injection production pattern, TK-3 connection shunt was the highest, TK-4 was the second highest.

**Reference**

[1] Kang YZ. Characteristics and Distribution Laws of Paleokarst Hydrocarbon Reservoirs in Palaeozoic Carbonate Formations in China, gas industries, 2018, 28(6): 1-12

[2] Qi LX, Yun L. Development characteristics and Main Controlling factors of the Ordovician carbonate karst in Tahe oil field, oil & gas geology, 2010, 31(1): 1-12

[3] Li Y, Fang ZH. Developmental pattern and distribution rule of the fracture-cavity system of Ordovician carbonate reservoirs in the Tahe Oilfield, Acta Petrolei Sinica, 2011, 32(1): 1-11

[4] Zhang XM, Yang J, Yang QL, Zhang CD. Reservoir description and reserves estimation technique for fracture-cave type carbonate reservoir in Tahe Oilfield, Acta Petrolei Sinica, 2004, 25(1):13-18

[5] Li Y. Ordovician carbonate fracture-cavity reservoirs identification and quantitative characterization in Tahe Oilfield, Journal of China University of Petroleum (Edition of Natural Science), 2012, 36(1): 1-7

[6] Qi LX. Exploration practice and prospects of giant carbonate field in the Lower Paleozoic of Tarim Basin, Oil & Gas Geology, 2014, 35(6): 771-779

[7] Huang TZ, Jiang HS, Ma QY. Hydrocarbon accumulation characteristics in Lower Paleozoic Carbonate reservoirs of Tarim Basin, Oil & Gas Geology, 2014, 35(6): 780-787

[8] LV HT, Ding Y, Geng F. Hydrocarbon accumulation patterns and favorable exploration areas of the Ordovician in Tarim Basin, Oil & Gas Geology, 2014, 35(6): 798-805

[9] Wang DP, Lu HM, Chen XL, et al. Petroleum accumulation systems and distribution of medium to large marine carbonate fields, Oil & Gas Geology, 2016, 37(2): 363-371

[10] Li Y. The theory and method for development of carbonate fractured-cavity reservoirs in Tahe oilfield, Acta Petrolei Sinica, 2013, 34(1): 115-121

[11] Wu WM, Zhan ZW, Ouyang D, et al. Research and Application of Multistage-section Water Plugging Technology in Fractured-cavity Carbonate Reservoirs, Journal of Southwest Petroleum University(Science & Technology Edition), 2015, 37(2): 119-124

[12] Wu WM, Ouyang D, Qing F, et al. Water shutoff technology for fractured vuggy reservoirs in carbonate reservoirs in Tahe Oilfield, Petroleum Geology and Recovery Efficiency, 2013, 6: 104-107,118

[13] Wang N. Application of tracer monitoring technology in oil field adjustment, Chemical Enterprise Management, 2017, 5: 25

[14] Lu XB, Rong YS, Li XB, et al. Construction of injection-production well pattern in fractured-vuggy carbonate reservoir and its development significance: A case study from Tahe oilfield in Tarim Basin, Oil & Gas Geology, 2017, 38(4):658-664