TOPOLOGY-BASED 3-D FRACTAL CHARACTERIZATION OF FRACTURE COMPLEXITY IN PROPAGATION EXPERIMENT

by

Hao YAN [a], ***Ran ZHANG*** [a,b,c*], ***Ju-Hui ZHU*** [d], ***Rong WANG*** [d], ***Qian-Kun REN*** [a], ***and Yong REN*** [d]

[a] School of Mechanical Engineering, Xihua University, Chengdu, China
[b] State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu, China
[c] State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, Beijing, China
[d] Downhole Service Company, CCDC, CNPC, Chengdu, China

Original scientific paper
https://doi.org/10.2298/TSCI230714021Y

The complexity of the fracture network, formed by the interaction of hydraulic fractures and natural fractures during hydraulic fracturing, is one of the important criteria for guiding shale gas field production. In this study, we selected the deep shale of the Longmaxi formation as the object of study. Through indoor hydraulic fracturing experiments and fracture 3-D reconstruction technology, we conducted a quantitative study on the complexity of the fracture network created by the influence of hydraulic and natural fractures interacting with each other during hydraulic fracturing. The results show that the fractal dimensions, average connection numbers of topological structure branches, and relative lengths of fracture intersections for hydraulic fractures in 10 groups of specimens are 1.93-2.27, 0-1.143, and 1.02-1.98, respectively.

Key words*: hydraulic fracture, complexity, fractal dimension, topological structure*

Introduction

China has abundant shale gas reserves in the eastern Sichuan Basin and surrounding areas at depths of around 3500-4500 m, and mainly enriched in the marine organic-rich shale of the Wufeng-Longmaxi formation. Deep shale reservoirs differ from their shallow counterparts that have already achieved large-scale development [1]. Conventional large-scale hydraulic fracturing technology is still the main technical means for deep shale gas development at present. However, the fracture propagation mechanism and law of deep shale reservoirs remain unclear. There is a lack of understanding leads to unsatisfactory hydraulic fracturing effects. Additionally, there is a deficiency in methods that can comprehensively characterize the complexity of fracture networks formed by the interaction of hydraulic fractures and natural fractures. Currently, the methods used to characterize the complexity of fracture networks include fracture density [2], fractal dimension [3], topology [4], and anisotropy parameters based on wave velocity [5]*, etc.*. Among these, the fractal dimension is effective in quantitatively describing the geometric shape, evolution property, and macroscopic mechanical behavior of rocks. Li *et al.* [6] used parameters such as fractal dimension and multifractal spectrum to quantitatively

* Corresponding author, e-mail: zhangran87@foxmail.com

evaluate the characteristics of shale porosity in the Wufeng-Longmaxi formation in the Jingmen exploration area. Sanderson *et al.* [4] used the concept of topology to describe and analyze 2-D and 3-D fracture networks, and proposed a classification method based on node types (*I*, *Y*, *X*). Mayerhofer *et al.* [7] proposed to use stimulated reservoir volume (SRV) as a dynamic parameter for wells.

However, these methods have some limitations. The fractal dimension can only quantitatively characterize the fracture distribution under similar fracture density conditions, and cannot indicate the connectivity of the fracture network. Topology cannot represent the distribution position and quantity of fractures [8]. Therefore, it is necessary to consider other parameters or characteristics to quantitatively characterize the complexity of fractures.

To overcome the limitations of existing evaluation methods, this study took Longmaxi formation outcrop shale as research object, carried out hydraulic fracturing experiment.

Sample preparation

The samples used in the experiment were collected from the Longmaxi formation shale outcrop in Changning County, Yibin City. The shale outcrop is shown in fig. 1(a). The material parameters measured at 120° and 70 MPa and the formation pressure around 4300 m are shown in tab. 1. Outcrop rock samples were collected and processed into standard square samples with a side length of 300 mm. A hole was drilled perpendicular to the shale bedding. The wellbore schematic and drilling processing schematic are shown in fig. 1(b).

(a)

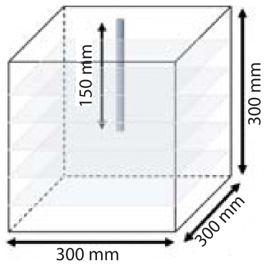
(b)


Figure 1. Outcrop collection (a) and specimen processing (b)

Table 1. The material parameters and the formation pressure

Young's modulus	Poisson's ratio	Compressive strength	Maximum stress	Minimum stress
37.3 MPa	0.215	13.7 MPa	120-130 MPa	95-110 MPa

Experimental scheme

Due to the limitation of the experimental equipment, the triaxial stress was designed according to the similarity principle [9]. The specific experimental parameters are shown in the tab. 2.

Experimental equipment and procedures

This experiment used the true triaxial physical model test system to conduct hydraulic fracturing simulation experiment. The experimental procedure is:
– Remove the rock debris and dust on the surface of the shale specimens.
– Load the lateral and axial pressure to the predetermined value.
– Pump the fracturing fluid, and record the bottomhole pressure in real time.
– Reconstruct the 3-D fracture network according to the fracture structure and size.

Table 2. Experimental parameters

Number	Maximum horizontal stress, σ_H [MPa]	Minimum horizontal stress σ_h [MPa]	Vertical stress σ_v [MPa]	Fluid viscosity [mPa·s]	Pumping rate [mlmin^{-1}]
1	18	15	20	3	20
2	18	15	20	20	20
3	18	15	20	3	20
4	18	15	20	20	20
5	18	5	20	20	40
6	18	5	20	3	40
7	18	5	20	3	40
8	18	5	20	3	40
9	18	15	20	20	40
10	18	15	20	3	40

The 3-D reconstruction of crack structures

We used the VG studio software to reconstruct the 3-D structure of fractures. As shown in fig. 2, it can be observed that hydraulic fractures mainly formed the following typical fracture modes: simple fracture like a straight line (1# and 2#), hydraulic fracture captured by horizontal bedding, like a *T* shape (3#, 4#, 5#, 6#), hydraulic fracture extended between two horizontal beddings, like an *H* shape (7#), and complex fracture formed by multiple natural micro-fractures (8#, 9#, 10#).

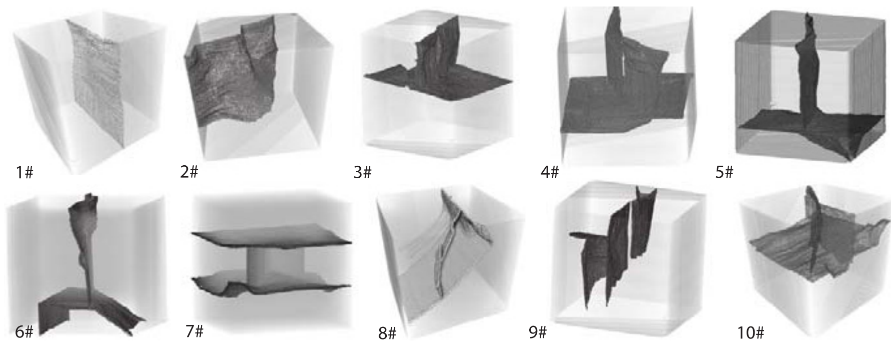


Figure 2. The 3-D reconstructed structure of cracks in 10 sets of specimens

Fractal dimension

According to the 3-D reconstruction structure of fractures, the box dimension method [10, 11] was used to quantitatively describe the fractal dimension of fractures.

According to the similar fractal theory:

$$\lg N_n = \lg C - D \lg \lambda_n \tag{1}$$

where $n = 1, 2, \ldots$, C is a proportion constant, and N_n, C, λ_n, and D are the all dimensionless quantities. Here, we fit a series of (λ_n, N_n) data into a straight line on a double logarithmic graph. The slope of the line is the fractal dimension, D.

Topological network

New branches and nodes are constantly generated during the fracture propagation process. The nodes and branches (X, Y, I) formed in the 2-D plane and 3-D space are shown in fig. 3.

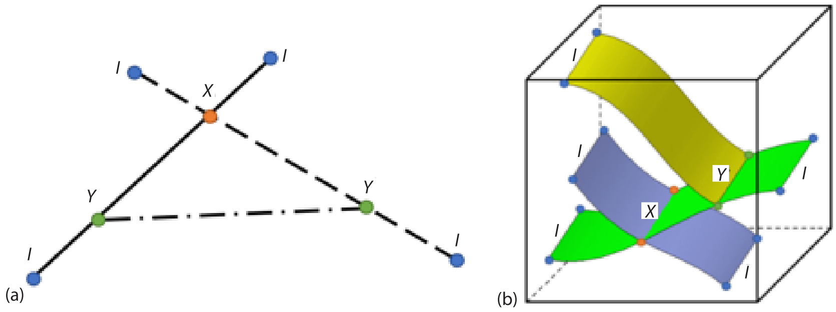


Figure 3. Topology in the 2-D plane (a) and topology in 3-D space (b)

The number of branches in a single fracture space and the average number of connections per branch can be expressed:

$$N_a = \frac{1}{2}\left(4N_X + 3N_Y + N_I\right) \quad \text{and} \quad N_b = \frac{6N_Y + 8N_X}{N_I + 3N_Y + 4N_X} \tag{2}$$

where N_I, N_Y, and N_X are the number of I-type, Y-type, and X-type intersection curves, respectively, and N_a and N_b are the number of branches and the average connection number of each branch, respectively.

Characterization of crack complexity in two dimensions

Based on the two quantitative characterization methods described in the previous section, all groups of experimental results were calculated and the results are shown in tab. 3.

Table 3. Fractal dimension and topology calculations for 10 groups of specimens

Number	Fractal dimension, D	Average number of connections, N_b	Number	Fractal dimension, D	Average number of connections, N_b
1	1.93299	0	6	2.18311	1
2	1.98914	0	7	2.16793	1.2
3	2.1409	1	8	2.19324	1.2
4	2.16399	1	9	2.2725	1.143
5	2.19449	1.2	10	2.21181	1

The fractal dimension and the average number of branch connections N_b are represented in a 2-D co-ordinate system, as shown in fig. 4.

The experimental groups with similar crack distributions have the same N_b values. Significantly, the fracture distribution of the experimental groups 8# and 5# is inconsistent, but the fractal dimension, D, and the average branch connection number, N_b, are very close, which brings confusion distinguish the two groups of experiments.

Relative length of crack intersecting lines

As mentioned earlier, since the fractal dimension and topological structure only describe the complexity of fractures from two characteristic parameters, there are still some limitations. Therefore, we introduce the length of intersecting lines of fracture surfaces as another essential feature for analyzing the complexity of fractures as shown in fig. 5. Determine the degree of connectivity of the seam network by counting the length of crack intersections corresponding to different nodes.

The length, L, of hydraulic fractures in 10 groups of specimens was counted. Since different sizes of specimens limit the extension of fractures, the ratio of fracture length to specimen edge length is given:

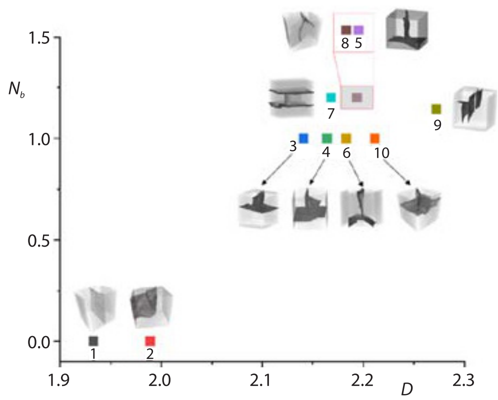


Figure 4. Characterization of the complexity of specimens in a 2-D co-ordinate system

$$L_r = \frac{L}{l} \tag{3}$$

where L_r is the relative length of fracture intersection-line, L – the hydraulic fracture intersection-line length, and l – the standard specimen edge length.

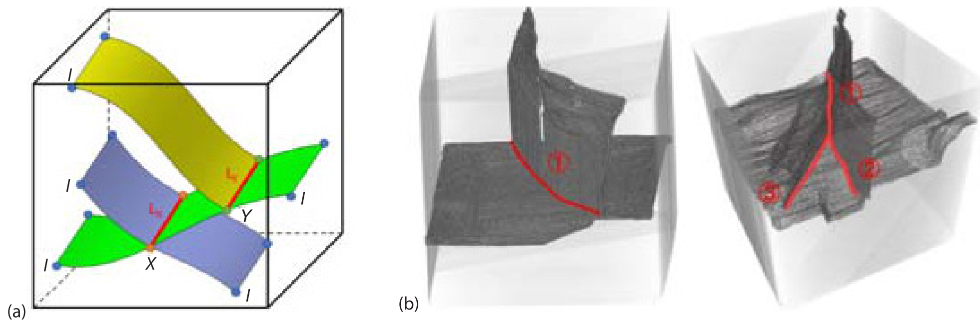


Figure 5. Schematic diagram of crack intersecting lines (a) and the red line is the intersecting line in the 3-D crack map (b)

Characterization of crack complexity in three dimensions

Referring to the previous characterization in the 2-D co-ordinate system, these three features are used as axes in the Cartesian co-ordinate system. Take the fractal dimension as X-axis, average branch connection number in topological structure as Y-axis, and relative length of fracture intersection-line as Z-axis. Then the corresponding positions of the fracture complexity of the 10 groups of specimens in the 3-D co-ordinate system were:

As shown in fig. 6, the complexity of specimen fractures can be judged by their relative positions. The closer to the co-ordinate origin the specimen is, the lower the complexity is, and the farther away from the co-ordinate origin the specimen is, the higher the complexity is. Compared with Jiang [12] and He *et al.* [13] 2-D co-ordinate system characterization model, this model can make the evaluation result more comprehensive.

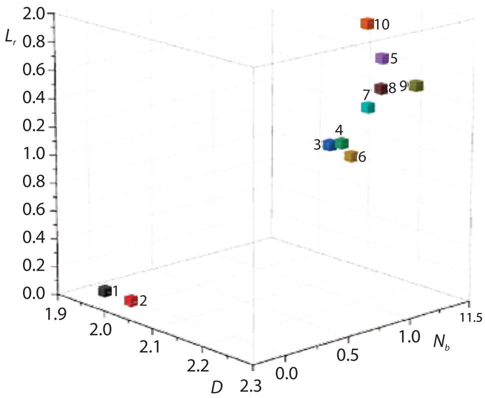


Figure 6. Characterization of crack complexity of 10 groups of specimens in a 3-D co-ordinate system

From the experimental results and the calculation of the complexity of the fracture network, they indicate that: Deep shale also has the potential to form complex fractures, and different parameters of hydraulic fracturing have different effects on the network of fractures formed. High displacement injection favors the activation of natural fractures and the formation of a complex network of seams. The experimental group species high discharge group obviously activated more natural fractures, and the calculated complexity was higher than that of the other groups. For the same fracturing fluid viscosity, the value of the intersection length of the fracture formed by the high displacement fracturing fluid group is significantly larger than that of the low displacement group. Therefore, increasing the displacement of fracturing fluid is beneficial for activating natural fractures, forming a complex fracture network. Field fracturing operations should increase the displacement of fracturing fluid within a reasonable range.

Conclusion

This paper present a approach to quantitatively study the complexity of deep shale hydraulic fractures based on hydraulic fracturing experiment and fracture 3-D reconstruction technology. The 2-D evaluation method based on fractal dimension and topological structure has some limitations, and it is limited to comprehensively characterize the complexity of the fracture network. The length of crack intersections is an effective way to quantitatively characterize the complexity of the network.

Nomenclature

D – fractal dimension, [–]
L – hydraulic fracture intersection-line length, [m]
l – standard specimen edge length, [m]

Greek symbol

λ_n – edge length, [m]

Acknowledgment

The authors would like to thank the National Natural Science Foundation of China (Grant No: 52004225), Application Foundation Project in Sichuan Province (2022NSFSC1273) and Open Fund (PRP/ open-2001) of National Key Laboratory of Petroleum Resources and Engineering for financial support and permission perceive this study.

References

[1] Li, S., *et al.*, Distribution Characteristics, Exploration and Development, Geological Theories Research Progress and Exploration Directions of Shale Gas in China, *China Geology*, *5* (2022), 1, pp. 110-135
[2] Cheng, T., *et al.*, Progress in Fracture Characterization And Prediction, *Science and Technology*, *31* (2013), 21, pp. 74-79
[3] Jie, F., *et al.*, Determination Fractal Dimension of Soil Macro-Pore Using Computed Tomography, *Journal of Irrigation and Drainage*, *24* (2005), 4, pp. 26-28
[4] Sanderson, D. J., *et al.*, The Use of Topology in Fracture Network Characterization, *Journal of Structural Geology*, *72* (2015), Mar., pp. 55-66
[5] Cardona, R., *et al.*, *Fracture Network Characterization from P-and S-Wave Data at Weyburn Field*, SEG, Houston, Tex., USA, 2003, p. SEG-2003-0370

[6] Li, X., *et al*., Micro-Pore Structure and Fractal Characteristics of Deep Shale from Wufeng Formation Longmaxi Formation in Jingmen Exploration Area, *Journal of Natural Gas Geoscience*, *7* (2022), 3, pp. 121-132

[7] Mayerhofer, M. J. J., *et al.*, What is Stimulated Reservoir Volume, *SPE Production and Operations*, *25* (2010), 01, pp. 89-98

[8] Miao, T., *et al*., A Fractal Analysis of Permeability for Fractured Rocks, *International Journal of Heat and Mass Transfer*, *81* (2015), Feb., pp. 75-80

[9] De, P., *et al*., Experimental Verification of Dimensional Analysis for Hydraulic Fracturing, *SPE Production and Facilities*, *9* (1994), 4, pp. 230-238

[10] Cao, T., *et al*., Characterization of Pore Structure and Fractal Dimension of Paleozoic Shales from the Northeastern Sichuan Basin, China, *Journal of Natural Gas Science and Engineering*, *35* (2016), Part A, pp. 882-895

[11] Sarkar, N., *et al.*, An Efficient Differential Box-Counting Approach to Compute Fractal Dimension of Image, I*EEE Transactions on Systems, Man, and Cybernetics*, *24* (1994), 1, pp. 115-120

[12] Jiang, C. B., *et al*., Experimental Study on Characterisation of Hydraulic Fracturing Coal Fracture Network and Assessment of Fracture-Making Performance, *Coal Science and Technology*, *51* (2023), 6, pp. 62-71

[13] He, Q., *et al*., Fractal Characterization of Complex Hydraulic Fractures in Oil Shale Via Topology, *Energies*, *14* (2021), 4, 1123

Paper submitted: July 14, 2023
Paper revised: August 27, 2023
Paper accepted: November 8, 2023