DUAL DIAGNOSTIC METHOD FOR FRACTURE MORPHOLOGY OF THERMAL COALBED METHANE RESERVOIR

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In most thermal coalbed methane production practices, the average single well production is low and the economic benefit is low. In order to improve the production of thermal coalbed methane (CBM), this paper presents a dual diagnosis method for fracture morphology of thermal CBM reservoir to improve hydraulic fracturing effect. The study is carried out as follows: Firstly, improved log-log curve method to adapt to coal seam fracturing construction. Secondly, establish the inclined stress calculation model of coal seam to obtain the critical depth value. Finally, combine the improved log-log method and critical depth method to form a dual diagnosis approach. Take Baiyang River in Xinjiang as an example, obtain the traffic, rock mechanics and other parameters suitable for the Baiyang River block, the fracture morphology is verified by fracturing data. The experimental results show that the approach can diagnose fracture morphology accurately.

Key words*: Coalbed methane; hydraulic fracturing; fracture morphology; log-log method; critical depth method; thermal*

1. Introduction

Some coal seam is well known for its three low characteristics: low permeability, low reservoir pressure and low gas saturation[1]. Hydraulic fracturing transformation technology is an effective method for increasing thermal coalbed methane production [2]. However, the low average single well output has become a major bottleneck for the development of thermal coalbed methane (CBM) industry in China. Therefore, how to increase the single well output and improve the development benefit is a technical issue which needs to be unraveled for the sound development of CBM industry of China.

Morphology of fracturing fracture is the core for CBM well fracturing to increase yield. In the process of fracturing, fracture type is directly related to the fracturing effect. Hydraulic fracturing may produce vertical fractures, horizontal fractures and complex fractures. In order to get the expected effect, diagnose the morphology of fracture accurately and selecting reasonable fracturing technology is needed.

The domestic and foreign scholars have carried out extensive research on the method of judging fracture morphology. PKN model[4-5] is applicable to long fractures of limited height with an elliptical vertical cross-section. KGD model[6-7],which is generally used for short fractures with a plane strain assumption. The Radial model is most appropriate when the total length is approximately equal to the height. The log-log slope of different types of net pressure and time can explain the types of various fractures and its extension modes. According to the log-log diagram of bottom net pressure and time, the relationship will be linear and the slope is e, different models correspond to different straight lines. Therefore, according to the different slope values of the line, it is possible to diagnose the fracture belongs to which model. The classic fracturing pressure analysis technology method is easy to operate, but this technique is not applicable to the interpretation of CBM fracturing data.

Another method is through calculation of crustal stress to diagnose. HBC first proposed a fracture morphology judgment model based on the minimum critical pressure of aperture walls in vertical fracture. Huang sums up the previous formulas for the determination of vertical fractures and horizontal fractures; However, these studies haven't consider coal seam with dip angle and the complex fractures such as T type fracture.

In summary, although many scholars have conducted the research on the hydraulic fracture morphology, but few scholars consider the fracture morphology in inclined coal seam. This paper presents a dual diagnosis method of coal seam fracture morphology by combining the log-log method and critical depth method. A computer program has been coded. Well test data from one northwest China Basin, which include all parameters needed in work, prove that the model established in this paper is reasonable and feasible.

2. Methodology

2.1. Fracture diagnostics from log-log method

The slopes in the Log-log relations of net pressure versus time, are characteristic of various types of fracture geometries and modes of propagation. The types of slopes and associated interpretations for vertical fractures are listed in Table 1. This table, in conjunction with the interpretation plot in Figue 1 shows that the log-log plot with its characteristic slopes

The classic fracturing pressure analysis technology method is not applicable to the interpretation of CBM fracturing data. This paper improve the classical log-log method to suit the coal seam fracturing.

The net pressure is defined as the difference between the bottom hole pressure and the closing pressure, while the closing pressure is equal to the minimum principal stress of the fracturing layer.

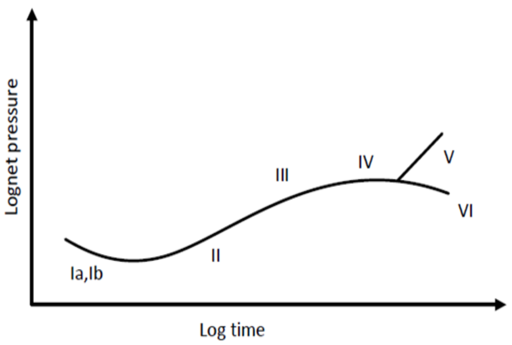

Fig. 1 Classical Log-log interpretation plot for various fracture propagation modes

Tab. 1 Interpretation of classic log-log plot fracture pressure slopes

Propagation Type	Log-log Slope	Interpretation

Ia	-1/6～-1/5	KGD
Ib	-1/8～-1/5	Radial
II	1/6～1/4	PKN
III	Reduced from II	Controlled height growth stress-sensitive fissure
IV	0	Height growth through pinch point fissure dilation T-shaped fracture
V	≥1	Restricted extension
VI	Negative following IV	Uncontrolled height growth

The net pressure formula is as follows:

$$P_F = P_p + P_H - P_f \quad (1)$$

The formula does not take into account the friction of the hole, because when the number of perforations is large or the diameter of the perforation hole is large, the hole friction resistance is close to 0, the field is almost satisfied.

For the fracturing of coal bed gas well commonly used 5.5 "casing. The formula for friction coefficient is:

$$\log f = 1.881785 \log Q - 0.898279 \quad (2)$$

The above formula is only suitable for pure fracturing fluid, so modify the formula for the friction coefficient of sand mixing fluid is needed. After analyzing the field data of fracturing, friction coefficient corrected by polynomial fitting:

$$f_r = -0.1448\rho_D^2 + 0.1094\rho_D + 1.0354 \quad (3)$$

Where $\rho_D = \frac{\rho_s}{\rho_p}$.

According to the deduction and verification, get the range of KGD model, Radial model and PKN model in coal seam fracturing, as Table 2 shows.

Tab. 2 The range of different models

Model	Range of e
KGD model	$-\frac{n}{2(n+1)} < e < -\frac{n}{n+2}$
Radial model	$-\frac{3n}{8(n+1)} < e < -\frac{n}{n+2}$
PKN model	$\frac{n}{4(n+1)} < e < -\frac{n}{2n+3}$

At present, coal seam fracturing often adopts two kinds of fracturing fluid system, namely active water and clean fracturing fluid. The flow index of the activity of water was 1, for the clean fracturing fluid, which belongs to the viscoelastic fracturing liquid, it can not be simply characterized by flow index. If the fracturing fluid is active water, the log-log slope of KGD model ranges from -1/3 to -1/4，the log-log slope of Radial model ranges from -1/3 to -3/16，the log-log slope of PKN model ranges from 1/8 to 1/5.

In view of the models have overlap, according to onshore vertical well hydraulic fracturing methods, the shut-in pressure (Pc) is considered to be equal to the minimum horizontal principal stress (σh), So this paper introduce the concept of net overburden pressure and the formula as follows:

$$\sigma_h = P_c \tag{4}$$

$$\overline{\sigma}_v = \sigma_v - P_c \tag{5}$$

In fracturing construction, the morphology of fracture can be judge by the positive and negative values of net overburden pressure. Combined Log-log curve of net pressure and time, if $\log\overline{\sigma} \le \log\sigma$, the fracture morphology is horizontal fracture; if $\log\overline{\sigma} > \log\sigma$, the fracture morphology is vertical fracture; if the front part of the curve is $\log\overline{\sigma} > \log\sigma$, the posterior part of the curve is $\log\overline{\sigma} < \log\sigma$, the fracture morphology is T type fracture. The interpretation of log-log method for coal seam as shown in Table 3.

Tab. 3 Interpretation of log-log method for coal seam

Log-log Slope	$\log\sigma - \log\overline{\sigma}$	Interpretation
-1/4～-1/3	>0	Vertical fracture(KGD model)
	<0	Horizontal fracture(Radial model)
-3/16～-1/3	<0	Horizontal fracture(Radial model)
1/8～-1/5	>0	Vertical fracture(PKN model)

2.2. Fracture diagnostics from critical depth method

Three directions stress (vertical stress, horizontal minimum principal stress and maximum horizontal principal stress) of inclined coal strata can be calculated as following formula:

$$\sigma_v = \int_0^H \rho(h) g dh \tag{6}$$

$$\sigma_h = \left(\frac{\gamma_s}{1-\gamma_s} + \xi_1\right)(\sigma_v - \alpha P_s)\cos\theta + (\sigma_v - \alpha P_s)\sin\theta\sin(\omega\text{-}\omega^0) + \alpha P_s \tag{7}$$

$$\sigma_H = \left(\frac{\gamma_s}{1-\gamma_s} + \xi_2\right)(\sigma_v - \alpha P_s)\cos\theta + (\sigma_v - \alpha P_s)\sin\theta\cos(\omega\text{-}\omega^0) + \alpha P_s \tag{8}$$

Vertical fracture fracturing pressure calculation formula (not considering filtration) is

$$P_v = 3\overline{\sigma}_h - \overline{\sigma}_H + S_t + P_s \tag{9}$$

Horizontal fracture fracturing pressure calculation formula (not considering filtration) is

$$P_h = \frac{\overline{\sigma}_v + S_t}{0.94} + P_s \tag{10}$$

Let the horizontal fracture fracturing pressure is equal to the vertical fracture fracturing pressure to calculate critical depth value.

3. Example of dual diagnosis method for fracture morphology of thermal coalbed reservoir

Taking BaiYang River block as an example to calculate and diagnose the fracture morphology, the process is shown in Figure 2.

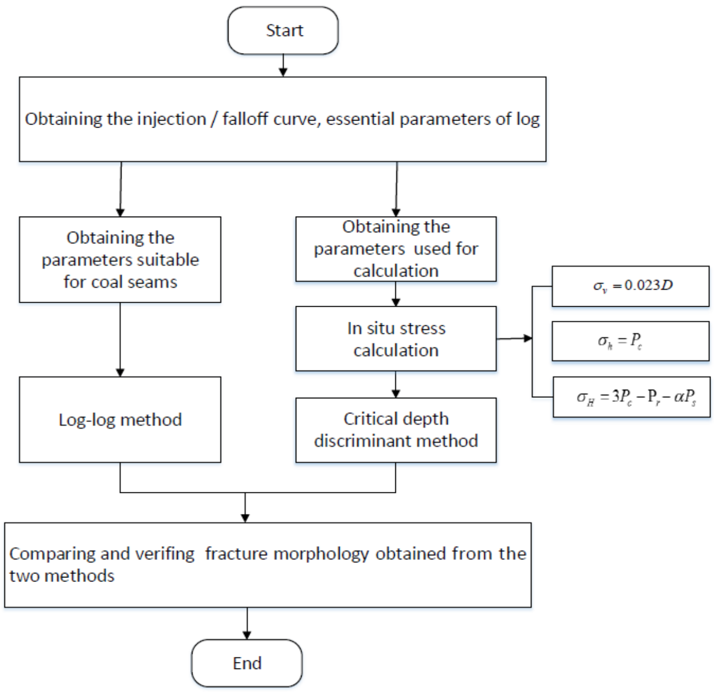

Fig. 2 Workflow for dual diagnosis method for fracture morphology

3.1. Log-log method

In this part, 42 layer in 11 well, 41 layer in 26 well and 42 layer in 47 well are selected to calculate and diagnose the fracture morphology on the compiled computer program.

The average depth of the 39 layer in 11 well is 650m, use active water in the whole process, the total amount is 1215 m3, quartz sand is 52 m3, sand ratio is 6.16%, working pressure is during 26.9-42.24Mpa, Fracturing pressure is 36.78 MPa, sand displacement is 8.5 m3/min. The fracturing construction curve diagram and the log-log diagram of the 39 layer in No.11 well are shown in Figure 3. As illustrated in Figure 3, the fracture morphology of 39 layer in No. 11 well is horizontal fracture.

The average depth of 42 layer in 26 well is 750m, use active water in the whole process, the total amount is 794.5 m3, quartz sand is 56 m3, sand ratio is 15.9%, working pressure is during 17.67-19.77MPa, No obvious rupture pressure, sand displacement is 8.5 m3/min. The fracturing construction curve diagram and the log-log diagram of the 42 layer in No.26 well are shown in Figure 4. As illustrated in Figure 4, the fracture morphology of 42 layer in No.26 well is vertical fracture.

The average depth of 41 layer in 47 well is 690m, use active water in the whole process, the total amount is 924 m3, quartz sand is 48 m3, sand ratio is 9.46%, working pressure is during 18.51-34.63 MPa, Fracturing pressure is 34.63 MPa, sand displacement is 7 m3/min. The fracturing construction curve diagram and the log-log diagram of the 41 layer in No.47 well are shown in Figure 5. As illustrated in Figure 5, the fracture morphology of 41 layer in No. 47 well is T type fracture.

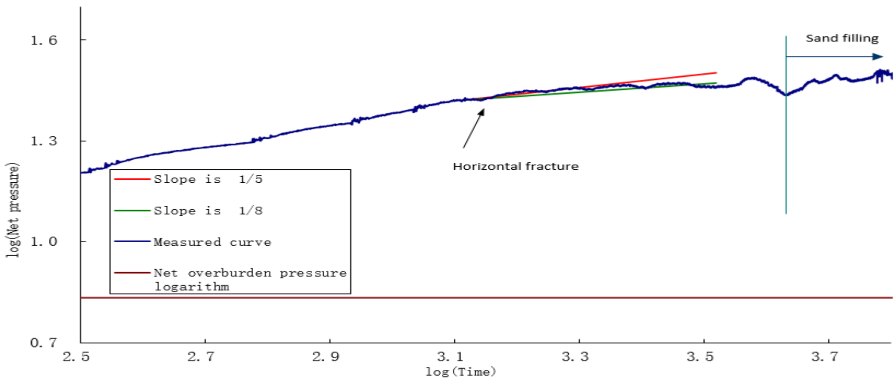

Fig. 3 The log-log curve diagram of 39 layer in No.11 well

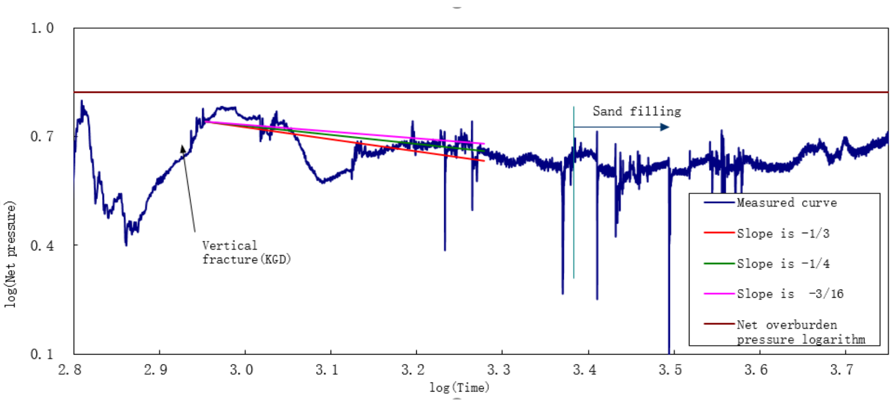

Fig. 4 The log-log curve diagram of 42 layer in No.26 well

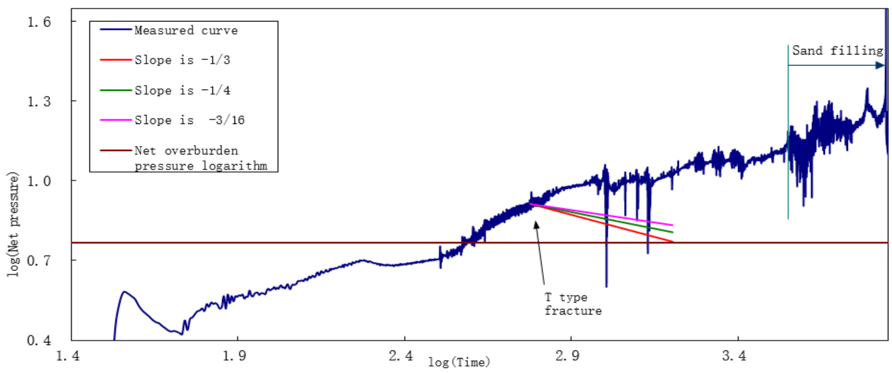

Fig. 5 The log-log curve diagram of 41 layer in No.47 well

3.2. Critical depth method

In this work, the 42 layer in 26 well is selected as an example to explain the calculation process in detail. Calculation of rock mechanical parameters and physical and mechanical properties by using acoustic logging data, some of them are listed in Table 4.

Tab. 4 Part results of rock mechanics

Depth (m)	Density (g/cm3)	longitudinal wave offset time ($\mu s/m$)	the transverse wave offset time ($\mu s/m$)	Dynamic Young's modulus (MPa)	Dynamic Poisson's ratio
602.9	1.3563	81	356	31512	0.4724
604	1.2553	99	533	13082	0.4822
606.1	1.2587	87	469	16991	0.4819
608.25	1.2693	124	648	8952	0.481
610.25	1.2747	123	632	9444	0.4805
612.75	1.6215	113	348	38599	0.4414
630.3	1.7819	82	221	103355	0.4205
634.75	1.6049	94	294	53731	0.4435
636	1.2934	120	594	10826	0.4787
638.15	1.3971	130	533	14464	0.4681
640.1	1.2701	126	655	8774	0.4809
642	1.3377	113	513	14972	0.4743
644.2	1.3215	128	597	10963	0.476
646.6	1.6769	83	244	80696	0.4343
684.4	1.9293	126	309	56630	0.4004
686	1.2841	126	634	9443	0.4796
688.05	1.2609	132	705	7521	0.4817
690.2	1.3175	129	606	10608	0.4764
692.5	1.2843	124	628	9639	0.4796
694.1	1.2709	128	668	8439	0.4808

Obtain conversion parameters of dynamic and static by means of linear regression, the dynamic and static Young's modulus conversion equation as follows:

$$E_s = 2387.7 + 0.6082 E_d \tag{11}$$

The dynamic and static Poisson's ratio conversion equation as follows:

$$\gamma_s = 0.0798 + 0.5278 \gamma_d \tag{12}$$

The coefficient of tectonic stress is calculated from the combination inversion of well No. 26 and No. 47, and get the coefficient of tectonic stress are 5.049*10-6 and 9.982*10-7.

The coal seam dip angle of 42 layer in No.26 is 48。, azimuth is 12。, substitute the parameters into Eq.9 and Eq.10, then get the average critical depth is 663.28m. So the fracture morphology of 42 layer in No.26 is vertical fracture.

Space lacks for a detailed description of No.11 well and No.47 well, through the same method, get the critical depth of No.11 well is 677.35 m and the critical depth of No.47 well is 704.66 m. So the fracture morphology of 39 layer in No.11 is horizontal fracture. So the fracture morphology of 41 layer in No.47 is vertical fracture.

Compare the results of the log-log method and critical depth method, the fracture morphology of 39 layer in No.11 well and 42 layer in No.26 well are consistent. The fracture morphology of 41 layer in No.47 is T type fracture by log-log method, it presents vertical fracture by critical method, Consider the limitation of the critical depth method, this paper diagnose that the fracture morphology of 41 layer in 47 well is T type fracture.

4. Experimental analysis

In this part, collect monitoring results for verification. The fracture monitoring results are shown in Figure 6, Figure 7 and Figure 8. As shown in Figure 6, the fracture monitoring result of the 39 layer in No.11 well is horizontal fracture. As shown in Figure 7, the fracture monitoring result of the 42 layer in No.26 well is vertical fracture. As shown in Figure 8, the fracture monitoring result of the 41 layer in No.47 well is T type fracture. The monitoring results are consistent with the results of dual diagnosis approach.

In order to analyze the accuracy of the dual diagnosis approach, collect the monitoring results of fracture in target layer. The results are shown in Table 5.

Table 5 shows that the 39 layer in No.47 well and 39 layer in No.50 are inconsistent, the coincidence rate is 83.3%.

In the above analysis, the approach can diagnose fracture morphology for coal seam fracturing accurately. The Fracture monitoring result is accurate, but the cost is very expensive. So the approach can reduce the cost of the process to diagnose fracture morphology in coal seam fracturing.

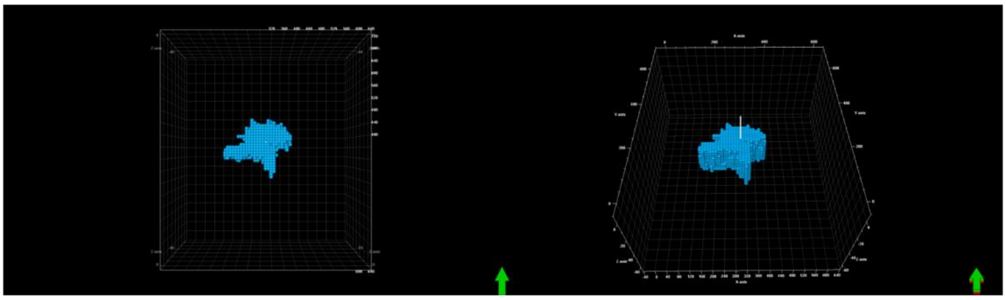

Fig. 6 Monitoring results of 39 layer in No.11 well

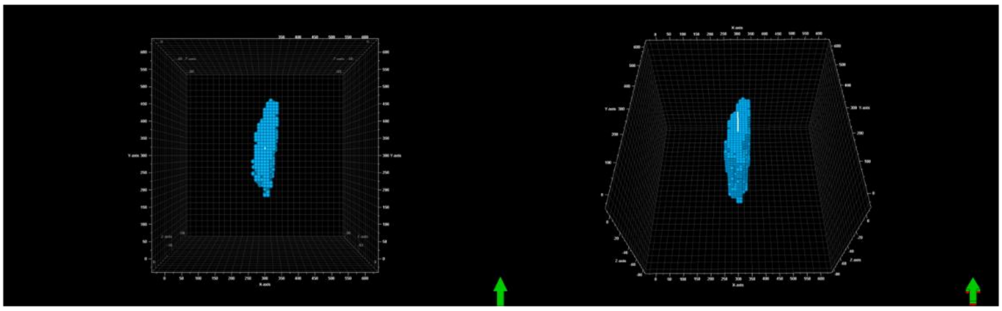

Fig. 7 Monitoring results of 42 layer in No.26 well

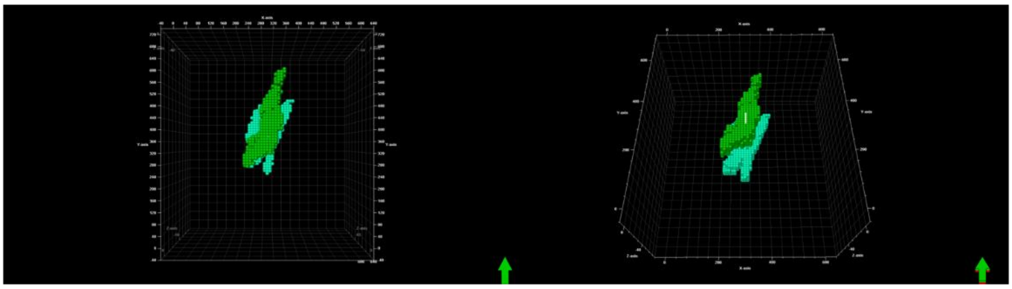

Fig. 8 Monitoring results of 41 layer in 47 well

Tab. 5 Comparison of fracture morphology

Well number	Layer	Fracture morphology (monitoring results)	Fracture morphology (analytical results)	Coincide
11	39	horizontal fracture	horizontal fracture	yes
11	41	horizontal fracture	horizontal fracture	yes
11	42	horizontal fracture	horizontal fracture	yes
26	39	horizontal fracture	horizontal fracture	yes
26	41	horizontal fracture	horizontal fracture	yes
26	42	vertical fracture	vertical fracture	yes
47	39	horizontal fracture	vertical fracture	no
47	41	T type fracture	T type fracture	yes
47	42	vertical fracture	vertical fracture	yes
50	39	vertical fracture	horizontal fracture	no
50	41	vertical fracture	vertical fracture	yes
50	42	vertical fracture	vertical fracture	yes

5. CONCLUSION

(1) The classical fracturing pressure analysis method is simple and easy to operate, but not applicable to the interpretation of CBM fracturing data. According to the deduction and verification, modify the friction coefficient of thermal coalbed methane fracturing, get the range of KGD model, Radial model and PKN model in coal seam fracturing, improve the classical log-log method to suit the coal seam fracturing.

(2) The principal stress model is not suit for inclined coal seam, improve the critical depth method to suit inclined coal seam.

(3) Combine the improved log-log method and critical depth method to form a dual diagnosis approach, the improved log-log method and critical depth method verify each other and complement each other, so that the dual diagnosis method can be used to diagnosis the fracture morphology effectively.

(4) Applied the dual diagnosis method to Baiyang River block of XinJiang, China, the diagnosis results are compared with the results of micro-seismic monitoring, the coincidence rate is 83.3%, which proves the correctness and practicability of this approach. Compared to micro-seismic monitoring, it can reduce the cost of the process to diagnose fracture morphology in coal seam fracturing.

Nomenclature

Nomenclature			
		γ_d	Dynamic Poisson's ratio
		E_d	Dynamic Young's modulus, MPa
e	The slope of Log-log relations of net pressure versus time	γ_s	Static Poisson's ratio
n	Fracturing fluid flow index	E_s	Static Young's modulus, MPa
P_F	bottom hole pressure, MPa	S_t	Tensile strength
P_p	wellhead pressure, MPa	α	Coefficient of Biot elasticity

P_H	hydrostatic fluid column pressure, MPa	ξ_1, ξ_2	Tectonic stress coefficient of coal seam
P_f	Friction along the path, MPa	P_s	Coal seam pressure, MPa
Q	displacement of fracturing construction, m^3/min	h	Depth of stratigraphic position, m
f	coefficient of friction resistance, MPa/1000m	σ_v	vertical stress, MPa
f_r	Coefficient of friction corrected by polynomial fitting	σ_h	Horizontal minimum principal stress, MPa
ρ_D	dimensionless density	σ_H	Horizontal maximum principal stress, MPa
ρ_s	Sand liquid density	H	Middle depth of coal seam, m
ρ_p	Sand liquid density	θ	Dip angle of coal seam
$\overline{\sigma}_v$	Net overburden pressure, MPa	ω	Azimuth of coal seam
P_c	Fracture closure pressure, MPa		

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