Where ρ_l is the density of fracturing fluid; h is the vertical depth from wellhead to fracturing section; dV_l is the infinitesimal volume of fracturing fluid.

3.3. The Elastic Strain Energy of Rock Body

The elastic strain energy of rock body per unit volume can be expressed as follows:

$$E_e = \int_0^{\varepsilon_e} \sigma(\varepsilon) d\varepsilon \tag{9}$$

Where ε_e is the strain when the elastic deformation of rock body terminates; $\sigma(\varepsilon)$ is the stress loading on the internal face of fracturing perforation.

The constitutional relationship of rock body in elastic deformation stage can be shown as follows:

$$\sigma(\varepsilon) = E\varepsilon \tag{10}$$

Where E is the Young's modulus of rock body.

3.4. The Damage Strain Energy of Rock Body

The strain energy of rock body damage deformation per unit volume can be expressed as follows:

$$E_p = \int_{\varepsilon_e}^{\varepsilon_b} \sigma(\varepsilon) d\varepsilon \tag{11}$$

Where ε_b is the damage strain before the rock body cracks.

According to the research results of literature [7] and literature [8] about damage degradation, combining formula (1), the rock body damage stress-strain constitutive equation can be expressed as follows:

$$\sigma(\varepsilon) = \left(1 - \sqrt{1 - \ln\left[1 + \frac{\omega(\varphi_0 - \varphi_\omega)}{1 - \varphi_0}\right]}\right) K \varepsilon^{\frac{1}{m}} \tag{12}$$

Where K, m is the material parameter of rock body.

4. THE FOLDING CATASTROPHE MODEL OF FRACTURES CRACKING

Substituting formula (7) and (8) into formula (6), expressing it using the differential form, and at the same time, being divided by $d\varepsilon$, the energy balance equation before rock body cracks can be obtained, which can be expressed as follows:

$$\frac{\eta d(Pt)}{d\varepsilon} + \frac{1}{2} \frac{gd\left(\rho_l \int_0^h dV_l\right)}{d\varepsilon} - \frac{\sigma(\varepsilon)}{E} \frac{d\sigma(\varepsilon)}{d\varepsilon} - \sigma(\varepsilon) = 0 \tag{13}$$

It can be concluded that the work that the fracturing pumps have done and the potential energy of fracturing fluid make the fractures cracking. When $\frac{\eta d(Pt)}{d\varepsilon} + \frac{1}{2} \frac{gd\left(\rho_l \int_0^h dV_l\right)}{d\varepsilon} > 0$, the rock body is under the energy accumulation state before cracking, and the elastic strain energy accumulation gradually shifts to damage strain energy accumulation, and the rock body is in a state without cracking. When $\frac{\eta d(Pt)}{d\varepsilon} + \frac{1}{2} \frac{gd\left(\rho_l \int_0^h dV_l\right)}{d\varepsilon} = 0$, it can be seen that without fracturing pump work and the gravitational potential energy of fracturing fluid, only the accumulation of elastic strain energy making the increasing of damage strain energy, until the rock body cracks. According to the analysis from Fig. (**1**) and Fig. (**2**), it can be concluded that there is a turning point $\tilde{\varepsilon}$ on the damage curve segment, which can satisfy the relationship $\sigma''(\tilde{\varepsilon}) = 0$. According to formula (12), the turning point $\tilde{\varepsilon}$ is the point where the value of second-order derivative of formula (12) is 0, which can be expressed as follows:

$$\begin{aligned} \sigma''(\tilde{\varepsilon}) = {} & \frac{1-m}{m^2} \tilde{\varepsilon}^{\frac{1}{m}-2} \left(1 - \sqrt{1 - \ln\left[1 + \frac{\omega(\varphi_0 - \varphi_\omega)}{1 - \varphi_0}\right]}\right) \\ & K + \frac{2}{m} \frac{d\left(1 - \sqrt{1 - \ln\left[1 + \frac{\omega(\varphi_0 - \varphi_\omega)}{1 - \varphi_0}\right]}\right)}{d\tilde{\varepsilon}} K \tilde{\varepsilon}^{\frac{1}{m}-1} \\ & + \frac{d^2\left(1 - \sqrt{1 - \ln\left[1 + \frac{\omega(\varphi_0 - \varphi_\omega)}{1 - \varphi_0}\right]}\right)}{d\tilde{\varepsilon}^2} K \tilde{\varepsilon}^{\frac{1}{m}} = 0 \end{aligned} \tag{14}$$

Making $\sigma(\varepsilon)$ and $\sigma(\varepsilon) \cdot d\sigma(\varepsilon)$ in the energy balance equation for the rock body that does not crack Taylor expansion at $\tilde{\varepsilon}$, and $\sigma''(\tilde{\varepsilon}) = 0$, it can be obtained the relationship as follows:

$$\sigma(\varepsilon) = \sigma(\tilde{\varepsilon}) + \sigma'(\tilde{\varepsilon}) \cdot (\varepsilon - \tilde{\varepsilon}) + \frac{\sigma'''(\tilde{\varepsilon})}{6} (\varepsilon - \tilde{\varepsilon})^3 + O(\varepsilon - \tilde{\varepsilon})^4 \tag{15}$$

$$\begin{aligned} \sigma(\varepsilon) \frac{d\sigma(\varepsilon)}{d\varepsilon} = {} & \sigma(\tilde{\varepsilon}) \cdot \sigma'(\tilde{\varepsilon}) + \left[\sigma'(\tilde{\varepsilon})\right]^2 (\varepsilon - \tilde{\varepsilon}) + \frac{\left[\sigma(\tilde{\varepsilon})\sigma'''(\tilde{\varepsilon})\right]}{2} (\varepsilon - \tilde{\varepsilon})^2 \\ & + \frac{\left[\left(3\sigma'(\tilde{\varepsilon}) + \sigma(\tilde{\varepsilon})\right)\sigma'''(\tilde{\varepsilon}) + \sigma(\tilde{\varepsilon})\sigma''''(\tilde{\varepsilon})\right]}{6} (\varepsilon - \tilde{\varepsilon})^3 + O(\varepsilon - \tilde{\varepsilon})^4 \end{aligned} \tag{16}$$

$$O(\varepsilon - \tilde{\varepsilon})^4 = 0 \tag{17}$$

The coefficient of $(\varepsilon - \tilde{\varepsilon})^2$ in formula (16) is $\frac{\left[\sigma(\tilde{\varepsilon})\sigma'''(\tilde{\varepsilon})\right]}{2}$, which is not equal to 0. According to the deterministic laws, substituting formula (15) and (16) into formula (13), and laying down the term whose order is higher than $(\varepsilon - \tilde{\varepsilon})^2$, it can be concluded:

$$\begin{aligned} & -\frac{1}{2}\left[(\varepsilon - \tilde{\varepsilon}) + \frac{\left[\sigma'(\tilde{\varepsilon})\right]^2}{\sigma(\tilde{\varepsilon}) \cdot \sigma'''(\tilde{\varepsilon})}\right]^2 + \\ & \frac{\left[\sigma'(\tilde{\varepsilon})\right]^4 + E\left(\frac{dW_b}{d\tilde{\varepsilon}} + \frac{dU_h}{d\tilde{\varepsilon}}\right)\sigma(\tilde{\varepsilon}) \cdot \sigma'''(\tilde{\varepsilon}) - \left[\sigma(\tilde{\varepsilon})\right]^3 \sigma'''(\tilde{\varepsilon})\left[\sigma'(\tilde{\varepsilon}) + E\right]}{\left[\sigma(\tilde{\varepsilon})\right]^2 \left[\sigma'''(\tilde{\varepsilon})\right]^2} = 0 \end{aligned} \tag{18}$$

According to formula (12), the relationship at $\tilde{\varepsilon}$ can be shown as follows:

$$\sigma(\tilde{\varepsilon}) = \left[\left(1 - \sqrt{1 - \ln\left[1 + \frac{\omega(\varphi_0 - \varphi_\omega)}{1 - \varphi_0}\right]}\right) K\right] (\tilde{\varepsilon})^{\frac{1}{m}} \tag{19}$$

$$\begin{aligned} \sigma'(\tilde{\varepsilon}) = {} & \frac{1}{m}\left(1 - \sqrt{1 - \ln\left[1 + \frac{\omega(\varphi_0 - \varphi_\omega)}{1 - \varphi_0}\right]}\right) K \tilde{\varepsilon}^{\frac{1}{m}-1} \\ & + \frac{d\left(1 - \sqrt{1 - \ln\left[1 + \frac{\omega(\varphi_0 - \varphi_\omega)}{1 - \varphi_0}\right]}\right)}{d\tilde{\varepsilon}} K \tilde{\varepsilon}^{\frac{1}{m}} \end{aligned} \tag{20}$$

$$\sigma'''(\tilde{\varepsilon}) = \frac{(1-m)(1-2m)}{m^3}\tilde{\varepsilon}^{\frac{1-3m}{m}}\left(1-\sqrt{1-\ln\left[1+\frac{\omega(\varphi_0-\varphi_\omega)}{1-\varphi_0}\right]}\right)K + \frac{3(1-m)}{m^2}\tilde{\varepsilon}^{\frac{1-2m}{m}}\frac{d\left(1-\sqrt{1-\ln\left[1+\frac{\omega(\varphi_0-\varphi_\omega)}{1-\varphi_0}\right]}\right)}{d\tilde{\varepsilon}}K + \frac{3}{m}\tilde{\varepsilon}^{\frac{1-m}{m}}\frac{d^2\left(1-\sqrt{1-\ln\left[1+\frac{\omega(\varphi_0-\varphi_\omega)}{1-\varphi_0}\right]}\right)}{d\tilde{\varepsilon}^2}K + \frac{d^3\left(1-\sqrt{1-\ln\left[1+\frac{\omega(\varphi_0-\varphi_\omega)}{1-\varphi_0}\right]}\right)}{d\tilde{\varepsilon}^3}\tilde{\varepsilon}^{\frac{1}{m}}K \tag{21}$$

The folding catastrophe model of rock body damage cracking in fracturing can be shown by formula (18).

The folding catastrophe model can be written in the standard form, which can be shown as follows:

$$x^2+\beta=0 \tag{22}$$

Where

$$x=(\varepsilon-\tilde{\varepsilon})+\frac{[\sigma'(\tilde{\varepsilon})]^2}{\sigma(\tilde{\varepsilon})\cdot\sigma'''(\tilde{\varepsilon})} \tag{23}$$

$$\beta=-2\left[\frac{[\sigma'(\tilde{\varepsilon})]^4+E\left(\frac{dW_b}{d\tilde{\varepsilon}}+\frac{dU_h}{d\tilde{\varepsilon}}\right)\sigma(\tilde{\varepsilon})\cdot\sigma'''(\tilde{\varepsilon})-[\sigma(\tilde{\varepsilon})]^3\sigma'''(\tilde{\varepsilon})[\sigma'(\tilde{\varepsilon})+E]}{[\sigma(\tilde{\varepsilon})]^2[\sigma'''(\tilde{\varepsilon})]^2}\right] \tag{24}$$

The two roots $x_u(<0)$ and $x_a=-x_u(>0)$ at any balance state in fracturing can satisfy the following relationship:

$$x_u=(\varepsilon-\tilde{\varepsilon})+\frac{[\sigma'(\tilde{\varepsilon})]^2}{\sigma(\tilde{\varepsilon})\cdot\sigma'''(\tilde{\varepsilon})}= -\sqrt{-2\left[\frac{[\sigma'(\tilde{\varepsilon})]^4}{[\sigma(\tilde{\varepsilon})]^2[\sigma'''(\tilde{\varepsilon})]^2}+\frac{E\left(\frac{dW_b}{d\tilde{\varepsilon}}+\frac{dU_h}{d\tilde{\varepsilon}}\right)}{\sigma(\tilde{\varepsilon})\cdot\sigma'''(\tilde{\varepsilon})}-\frac{\sigma(\tilde{\varepsilon})[\sigma'(\tilde{\varepsilon})+E]}{\sigma'''(\tilde{\varepsilon})}\right]} \tag{25}$$

$$x_a=(\varepsilon-\tilde{\varepsilon})+\frac{[\sigma'(\tilde{\varepsilon})]^2}{\sigma(\tilde{\varepsilon})\cdot\sigma'''(\tilde{\varepsilon})}= \sqrt{-2\left[\frac{[\sigma'(\tilde{\varepsilon})]^4}{[\sigma(\tilde{\varepsilon})]^2[\sigma'''(\tilde{\varepsilon})]^2}+\frac{E\left(\frac{dW_b}{d\tilde{\varepsilon}}+\frac{dU_h}{d\tilde{\varepsilon}}\right)}{\sigma(\tilde{\varepsilon})\cdot\sigma'''(\tilde{\varepsilon})}-\frac{\sigma(\tilde{\varepsilon})[\sigma'(\tilde{\varepsilon})+E]}{\sigma'''(\tilde{\varepsilon})}\right]} \tag{26}$$

According to the standard form of formula (22), when $a>0$, the equation is meaningless. When $a\le 0$, with the different value of a, the value of x is different, which constitutes a parabolic curve. The arbitrary symmetric solutions of the corresponding two point on the parabolic curve express the two equilibrium state of the fracturing of rock body. When x<0, in other words $(\varepsilon-\tilde{\varepsilon})<\frac{-[\sigma'(\tilde{\varepsilon})]^2}{\sigma(\tilde{\varepsilon})\cdot\sigma'''(\tilde{\varepsilon})}$, it is corresponding with the down branch of the parabolic curve. When x>0, in other words $(\varepsilon-\tilde{\varepsilon})>\frac{-[\sigma'(\tilde{\varepsilon})]^2}{\sigma(\tilde{\varepsilon})\sigma'''(\tilde{\varepsilon})}$, it is corresponding with the up branch of the parabolic curve. The greater of the value of $|a|$, the greater of the difference value between two symmetric solutions on up and down branch, and it is not easily for the rock body to develop from one balance state to another balance state, that is, the farther distance from rock body bursting. With the increasing of the work that fracturing pumps have done and the potential energy of fracturing fluid, the value of $|a|$ is decreasing, and x develops from down branch to the origin (as shown in Fig. (**3**)).

It can be concluded from the analysis of the mechanics behavior of fracturing rock body bursting that when the body catastrophe burst, it can satisfy that $\frac{dW_b}{d\tilde{\varepsilon}}+\frac{dU_h}{d\tilde{\varepsilon}}=0$. The value of branch point ($x_1(<0)$ and $x_2=-x_1(>0)$) can be expressed as follows:

$$x_{u\left(\frac{dW_b}{d\tilde{\varepsilon}}+\frac{dU_h}{d\tilde{\varepsilon}}=0\right)}=(\varepsilon-\tilde{\varepsilon})+\frac{[\sigma'(\tilde{\varepsilon})]^2}{\sigma(\tilde{\varepsilon})\cdot\sigma'''(\tilde{\varepsilon})}= -\sqrt{-2\left[\frac{[\sigma'(\tilde{\varepsilon})]^4}{[\sigma(\tilde{\varepsilon})]^2[\sigma'''(\tilde{\varepsilon})]^2}-\frac{\sigma(\tilde{\varepsilon})[\sigma'(\tilde{\varepsilon})+E]}{\sigma'''(\tilde{\varepsilon})}\right]} \tag{27}$$

$$x_{a\left(\frac{dW_b}{d\tilde{\varepsilon}}+\frac{dU_h}{d\tilde{\varepsilon}}=0\right)}=(\varepsilon-\tilde{\varepsilon})+\frac{[\sigma'(\tilde{\varepsilon})]^2}{\sigma(\tilde{\varepsilon})\cdot\sigma'''(\tilde{\varepsilon})}= \sqrt{-2\left[\frac{[\sigma'(\tilde{\varepsilon})]^4}{[\sigma(\tilde{\varepsilon})]^2[\sigma'''(\tilde{\varepsilon})]^2}-\frac{\sigma(\tilde{\varepsilon})[\sigma'(\tilde{\varepsilon})+E]}{\sigma'''(\tilde{\varepsilon})}\right]} \tag{28}$$

Integrating formula (22), the total potential energy function of folding catastrophe model for fracturing rock body can be shown as follows:

$$\Pi=\frac{1}{3}x^3+\beta x \tag{29}$$

The critical equilibrium state point (x_u) before the rock body cracks satisfies the following relationship:

$$\Pi_u=\frac{1}{3}x_u^3+\beta x_u \tag{30}$$

The equilibrium state point (x_a) after the rock body cracks satisfies the following relationship:

$$\Pi_a=\frac{1}{3}x_a^3+\beta x_a \tag{31}$$

According to the laws of Dirichlet, when $x<0$ and $\frac{\partial^2\Pi}{\partial x^2}<0$, the system is under unstable state. When $x>0$ and $\frac{\partial^2\Pi}{\partial x^2}>0$, the system reaches a new steady state. If x transits from down branch to up branch through origin point, the damage of the rock body is asymptotic expression. If x transits suddenly from down branch to up branch through a certain point, the damage of the rock body is catastrophe bursting, and the value of energy release can be shown in Fig. (**3**).

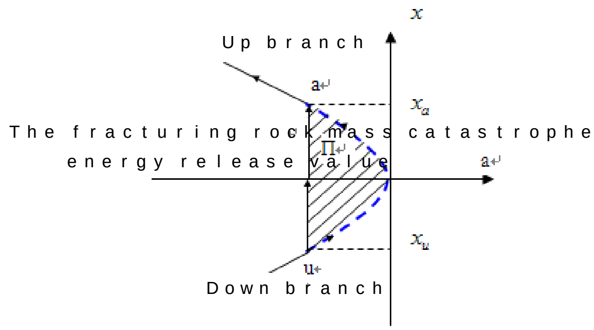

Fig. (3). The rock body catastrophe bursting in hydraulic fracturing.

When the body transits from x_u to x_a, the rock body become instability bursting, forming cracks, and the energy release value can be shown as follows:

$$\Delta\Pi = \frac{1}{3}\left(x_a^3 - x_u^3\right) + \beta\left(x_a - x_u\right) \tag{32}$$

Where $x_a = -x_u$, $x_a^2 = x_u^2 = -\beta$. By regularizing, the energy release value when the rock body transits can be shown as follows:

$$\Delta\Pi = -\frac{4}{3}x_a^3 = -\frac{4}{3}\left[2\left[\frac{\sigma(\tilde{\varepsilon})\left[\sigma'(\tilde{\varepsilon})+E\right]}{\sigma'''(\tilde{\varepsilon})} - \frac{\left[\sigma'(\tilde{\varepsilon})\right]^4}{\left[\sigma(\tilde{\varepsilon})\right]^2\left[\sigma'''(\tilde{\varepsilon})\right]^2}\right]\right]^{\frac{3}{2}} \tag{33}$$

Formula (33) is the model for calculating energy release value when the rock body burst suddenly and form hydraulic fractures in the process of fracturing.

5. THE CALCULATION OF CRACKS PROPAGATION PARAMETER

Assuming that the crack is open type fracture, which can be shown in Fig. (**4**).

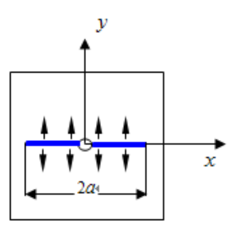

Fig. (4). The schematic diagram of crack propagation.

According to the geometric relations in the figure, the relationship between the energy release of rock body and crack propagation length can be shown as follows:

$$\Delta\Pi = 2\int_0^a G\,dA = 2\frac{\left(1-\nu^2\right)}{E}\int_0^a K_{\mathrm{I}}^2\,da \tag{34}$$

Where

$$K_{\mathrm{I}} = \sigma\left(\tilde{\varepsilon}\right)\sqrt{\pi a} \tag{35}$$

Where K_I is stress intensity factor; a is crack propagation length.

6. CASE STUDY

A certain research block in Daqing oil field was selected for experiment. The experimental cores were obtained by sealed coring from 1408.44～1440.98m, 1707.74～1739.59m and 849.17-976.63m three intervals. The cores were divided into three groups. According to rock mechanical test requirement, the rock mechanical parameters were measured respectively, and the measurement results can be shown in Table **1**. According to the measured results, we made the cores by ourselves, and conducted fracturing test. The energy release value when the rock body bursting suddenly and fractures propagation parameters were calculated, the results can be shown in Table **2**. The measured related results were shown in the below figure.

According to the rock body at different depth in a certain block of Daqing oil field, using the folding catastrophe model proposed in this paper, the cracks propagation energy release value of damaged rock body was calculated, and on this basis, the rock body cracks propagation length was calculated, and the accuracy of the model is verified by laboratory test, which was shown in Table **2**. By comparison, the maximum error between theoretical and the actual result is 9.71%. The new calculation method is in good agreement with the actual.

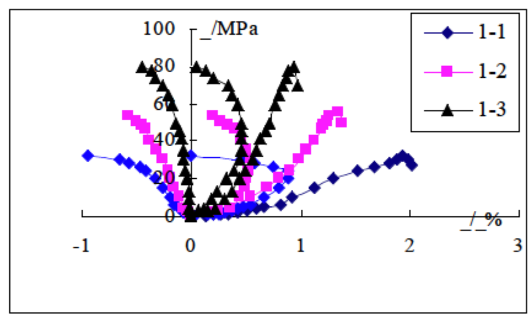

Fig. (5). The axial strain, radial strain and volume strain curves of group 1 cores.

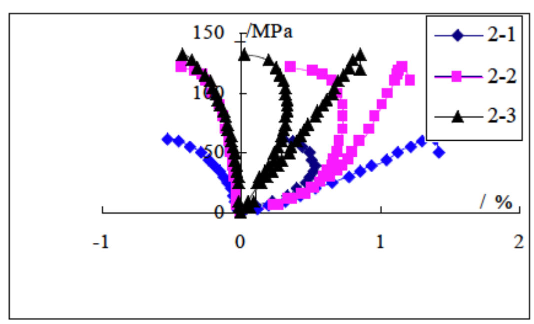

Fig. (6). The axial strain, radial strain and volume strain curves of group 2 cores.

CONCLUSION

(1) The cracks propagation calculation model in fracturing was established basing on catastrophe theory. The energy release value and cracks propagation parameters calculation model when the rock body bursting suddenly and form cracks were established basing on principle of conservation of energy.

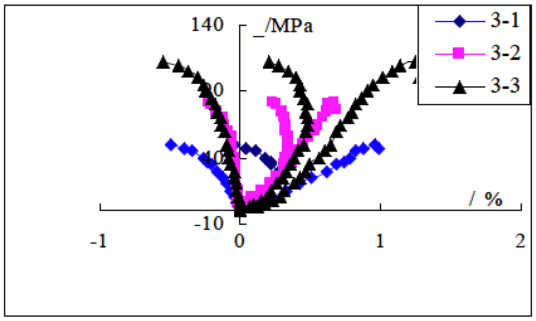

Fig. (7). The axial strain, radial strain and volume strain curves of group 3 cores.

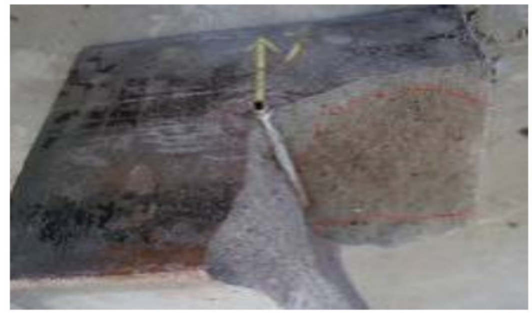

Fig. (8). The fracturing results of laboratory test of group 1 cores.

Fig. (9). The fracturing results of laboratory test of group 2 cores.

Fig. (10). The fracturing results of laboratory test of group 3 cores.

Table 1. The experimental results of rock parameters.

Core Number	The Group Number of Test Item	The Minimum Principal Stress (MPa)	Poisson's Ratio	Young's Modulus (MPa)	Material Parameters (m)	Material Parameters (*k*)
Cores of group 1 (1408.44 ~ 1440.98m)	1-1	29.4	0.21	18233	1.45	16300
	1-2	29.4	0.23	18645	1.45	16450
	1-3	29.7	0.23	11983	1.60	16230
Cores of group 2 (1707.74 ~ 1739.59m)	2-1	32.1	0.24	25907	1.20	19000
	2-2	32.3	0.20	19412	1.40	19100
	2-3	32.4	0.19	16577	1.50	19000
Cores of group 3(849.17-976.63m)	3-1	20.1	0.27	8623	1.70	15210
	3-2	20.1	025	8900	1.70	15200
	3-3	16.1	0.24	8720	1.70	15000

Table 2. The comparative results between calculated fractures length and actual value.

Test Item Number	The Group Number of Test Item	The Dimension of Test Item (cm^3)	The Strain Value of Rock Body Catastrophe Bursting	(J) The Energy Release Value	The Theoretical Fractures Propagation Semi-length (cm)	The Experimental Fractures Propagation Semi-length (cm)	Proportional Error (%)
Test item 1	1-1	30*30*30	0.0051	-227.08	13.978	12.90	7.71
	1-2	30*30*30	0.0048	-201.66	13.642	12.80	6.17
	1-3	30*30*30	0.0048	-312.84	13.622	12.30	9.71

(Table 2) contd….

Test Item Number	The Group Number of Test Item	The Dimension of Test Item (cm^3)	The Strain Value of Rock Body Catastrophe Bursting	(J) The Energy Release Value	The Theoretical Fractures Propagation Semi-length (cm)	The Experimental Fractures Propagation Semi-length (cm)	Proportional Error (%)
Test item 2	2-1	30*30*30	0.0049	-381.88	13.057	12.40	4.96
	2-2	30*30*30	0.0048	-364.80	10.641	11.00	-3.37
	2-3	30*30*30	0.0051	-412.84	10.440	11.10	-6.32
Test item 3	3-1	30*30*30	0.0054	-326.62	13.658	15	/
	3-2	30*30*30	0.0054	-340.14	15.841	15	/
	3-3	30*30*30	0.0056	-305.84	13.559	14.30	-5.47

(2) The cracks propagation energy release value and propagation length of different depth reservoirs were calculated, according to the rock body in a certain block of Daqing oil field. The maximum error between theoretical and the actual result is 9.71%. The calculated cracks propagation parameters basing on catastrophe theory is in good agreement with the experimental ones.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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