A NEW FRACABILITY EVALUATION MODEL FOR COMPLEX LITHOLOGIES FRACTURED SHALE OIL RESERVOIR

by

Ran ZHANG [a,b,c], ***Cheng-Jun LV*** [a*], ***Qian-Kun REN*** [a],
Yang WANG [a], ***Yang LIAO*** [a], ***and Zishan ZHANG*** [a]

[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

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Manufacturing knowledge can be preserved through knowledge accumulation and continuous integration. In order to improve the using efficiency of manufacturing knowledge, this knowledge is stored and used in the way of Knowledge graph. This paper will study the construction of Knowledge graph based on manufacturing process methods and the ability of Knowledge graph to provide services. This kind of manufacturing knowledge capability not only provides the manufacturing realization method of processing technology, but also can correspond to the design realization method of design graphics, providing theoretical support for the integrated realization of design and manufacturing process.

Key words: *fracability, shale oil, brittleness, fracture morphology, natural fracture*

Introduction

Since 2010, unconventional petroleum has become a crucial part of China's petroleum resources. With the continuous breakthrough of new technologies, a series of progress has been made in unconventional petroleum.

Shale oil is one of the typical representatives of unconventional petroleum. The physical properties of shale reservoirs are poor, and the porosity and permeability are low. Only by stimulation of hydraulic fracturing can it be effectively developed. Volume fracturing Technology improves seepage channels and seepage ability of reservoirs by injecting large-displacement, low viscosity fracturing fluid into formations to form multi-branched hydraulic fractures and connected fracture systems [1, 2]. The fracability fracture index is a key parameter to evaluate the fracture network complexity which is significant for fracturing candidate selection. Most studies at home and abroad regard brittleness as fracturability, believing that the stronger the brittleness of the reservoir, the more likely it is to generate a fracture network after fracturing, and do not consider the influence of natural fractures and in-situ stress [3-5]. Some shale oil reservoirs in China have strong heterogeneity and complex lithological changes, so it is very important to study the fracability evaluation method of complex lithological shale reservoirs for shale oil development.

[*] Corresponding author, e-mail: 2501437248@qq.com

Reservoir

In order to study the fracture propagation law of complex lithologies shale oil reservoir with multiple fractures, Kong 2 member (Ek_2) oil of Cangdong sag in Dagang Oilfield has been chosen as the study object. The rocks there contain mud shales, sandstones, carbonate rocks and transitional mixed rocks, with complex and varied lithology, strong heterogeneity, and the development featuring bedding and natural fractures. The main characteristics of reservoir rocks are low porosity and extra-low to ultra-low permeability. The porosity is 5.09% to 10.51% and the permeability is 0.44 to 6.84 mD.

The lithology in Ek_2 is complicated, and the heterogeneity of the rock is strong: quartz minerals (27.14%), plagioclase (17.57%), clay minerals (16.85%), dolomite (14.26%), calcite (10.77%), with the content of pyrite being the least. The Young's modulus of Ek_2 rocks are between 4 734 MPa and 54 502 MPa, and its average value is 17 743 MPa. The Poisson's ratio is between 0.118 and 0.446, and its average value is 0.267. Under the same confining pressure, Young's modulus and Poisson's ratio very much. The average dip angle is 24° and fractures with the dip angle less than 45° account for 81.5%. Most of natural fractures have obvious filling characteristics, with different degrees of quartz and calcite filling. The average azimuth angle is 34.8° (with the direction of maximum horizontal principal stress prevailing).

Brittleness index

According to the experience of North American shale development, Rickman brittleness index was selected as the main basis for fracability evaluation of Ek_2 shale oil reservoir in Dagang Oilfield. Rickman index is applied to evaluate the complexity of brittle fracture of rocks through Young's modulus and Poisson's ratio [6]. Specific to the natural fracture development, Rickman brittleness cannot effectively guide the fracturing design. Therefore, after fracturing stimulates in Dagang Oilfield Ek_2 member of reservoir, the output failed to reach the expectation.

According to the curve of the process of rock failure, it can be judged whether rock has brittle fracture through peak strain; according to Young modulus, the rock's ability to resist deformation can be described. The deformation rate can be described according to the shear dilatancy angle. A new brittleness evaluation model can be established through these three parameters with corresponding weights, which can be used to reflect the characteristic of the whole stress-strain process.

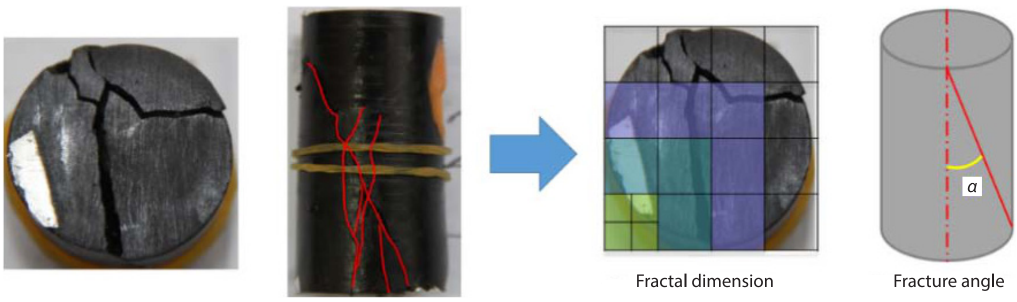


Figure 1. Fracture complexity characterization

It can be seen from the fig. 1 that the mode of the failure of core sample under triaxial compression test includes tensional (or fragile) fracture, shear fracture and transtensional composite fracture. In view of this, fractal theory is introduced to quantitatively describe the fracture complexity [7, 8]. Fractal box dimension is defined to describe the fracture complexity of core edge. Tensile fracture characteristics are described by fracture angle. Quantitative description of rock fracture complexity is given:

$$F_C = D\left(1-\frac{\alpha}{90}\right) \tag{1}$$

where F_C is the factor of describing rock fracture complexity, D – the fractal dimension, and α – the fracture angle. Peak strain is the strain when rock is fractured, and the size of peak strain is the judgment value of brittle fracture [9]. Shear dilatancy angle is the parameter representing material expansion, which has reflected the development state of cracks in rock fracture process. The shear dilatancy angle ψ is generally calculated:

$$\psi = \arcsin\frac{\Delta\varepsilon_v^p}{\Delta\varepsilon_v^p - 2\Delta\varepsilon_1^p} \tag{2}$$

where $\Delta\varepsilon_1^p$ is the plastic axial strain increment and $\Delta\varepsilon_v^p$ – the plastic volumetric strain increment.

Meanwhile, the correlation between fracture complexity and the rest of parameters such as mineral content are poor according to the calculation results. Therefore, the brittleness evaluation method suitable for shale is shown:

$$B_I = W_1E_n + W_2\psi_n + W_3\varepsilon_{pn} \tag{3}$$

where B_I is the brittleness index, and E_n, ψ_n, and ε_{pn} are the normalized Young modulus, shear dilatancy angle and peak strain.

The normalization calculation formulas of E_n, ψ_n, and ε_{pn}:

$$E_n = \frac{E-E_{\min}}{E_{\max}-E_{\min}},\quad \psi_n = \frac{\psi-\psi_{\min}}{\psi_{\max}-\psi_{\min}},\quad \varepsilon_{pn} = \frac{\varepsilon_{p\max}-\varepsilon_p}{\varepsilon_{p\max}-\varepsilon_{p\min}} \tag{4}$$

Adopt the grey correlation method to calculate and obtain all parameter weight coefficients of shale reservoir in Dagang Oilfield: $W_1 = 0.262$, $W_2 = 0.353$, and $W_3 = 0.385$.

The relation between the brittleness index and rock fracture complexity has been drawn and the comparison between Rickman brittleness evaluation methods has been taken, fig. 2. It can be seen that the model put forward this time can better reflect the complexity of rock fracture.

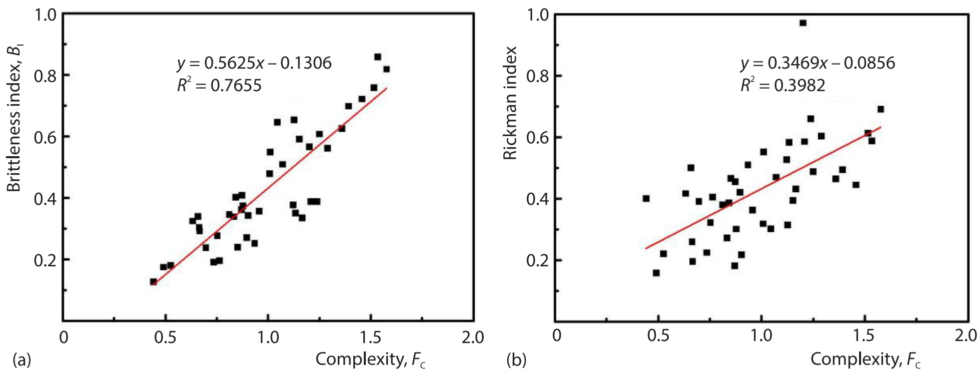


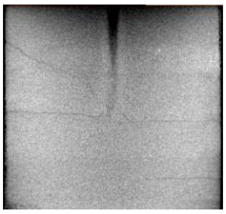
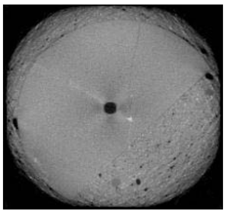
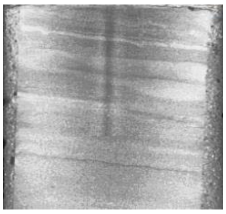
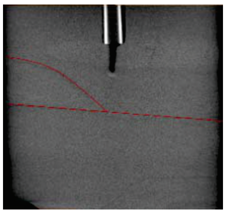
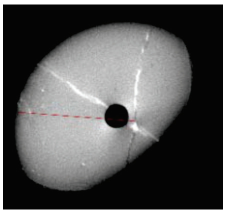
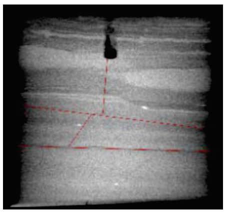
Figure 2. Relation between brittleness index and rock fracture complexity; (a) brittleness model in this paper and (b) rickman brittleness model

Fracability

Fracability is controlled by the reservoir and engineering factors including rock brittleness, stress difference, natural fracture and so on. Nature fracture and in-situ stress significantly influence the fracture geometry [10-12]. In view of this, core samples from Cangdong shale reservoirs with natural fractures were selected for the true triaxial hydraulic fracturing experiment.

Table 1 shows the changes of natural fractures and new fractures observed by CT scanning after the fracturing of cores No. 43, No. 44, and No. 45. Among them, the natural fractures of cores No. 43 and No. 45 are opened after fracturing, but there are no obvious visible new fractures and the natural fracture in core No. 44 fails to open. So the conclusion can be drawn that the main controlling factors for natural fracture opening are approaching angle and stress difference.

Table 1. Comparison of fractures before and after experiment by CT scan

Core	No. 43		No. 44		No. 45	
	Approaching angle	Stress difference	Approaching angle	Stress difference	Approaching Angle	Stress difference
	15°	4 Mpa	72°	4 Mpa	81°	0.5 Mpa
Before fracturing						
After fracturing						

According to fracture propagation theory, under the situation that the other conditions are the same, the linear fracture propagation requires the minimum fluid pressure and hydraulic fracture tip pressure, P, is represented:

$$P = \sigma_3 + \sqrt{\frac{\pi E\gamma}{2L(1-\nu^2)}} \tag{5}$$

where E is the Young's modulus of rock of target section stratum, ν – the Poisson's ratio of rock of target section stratum, γ – the surface energy of fracture, and L – the half length of hydraulic fracture:

$$(\sigma_1 - \sigma_3)\sin^2\theta = \left[\frac{\pi E\gamma}{2L(1-\nu^2)}\right]^{1/2} \tag{6}$$

where $E\gamma/(1-\nu^2)$ has represented the ability of forming fracture. The smaller the value is, it means that the rock is easier to form complex fractures. That is to say, the smaller the value of $(\sigma_1 - \sigma_3)\sin^2\theta$ is, the rock is easier to form complex fractures. Therefore, it can be taken as the fracability index when considering the natural fracture opening. The influencing index of natural fracture can be defined:

$$F_n = 1 - \frac{(\sigma_H - \sigma_h)\sin^2\theta}{\sigma_{nm}} \tag{7}$$

where F_n is the influencing factor of natural fracture opening, θ – the approaching angle, and σ_{nm} – the maximum value of $(\sigma_H - \sigma_k)\sin^2\theta$ in target block.

The horizontal stress difference influences the fracture complexity caused by fracture extension and diversion, so the in-situ stress index shall be defined:

$$S_I = 1 - \frac{\sigma_H - \sigma_h}{\Delta\sigma_m} \tag{8}$$

where $\Delta\sigma_m$ is the maximum value of horizontal stress difference in target block.

Therefore, by considering the rock brittleness, in-situ stress difference and natural fractures, the fracability evaluation model of shale oil reservoir is established:

$$F_I = B_I(w_4 F_n + w_5 S_I) \tag{9}$$

where F_I is the fracability index. The weight coefficient of natural fracture and in-situ stress index can also be calculated by the grey correlation method. It is obtained that w_4 = 0.52 and w_4 = 0.48. Under general condition, the weight can be given as 0.5.

Verification

True triaxial fracturing experiment

According to the results of true triaxial hydraulic fracturing experiment, Rickman brittleness index and fracability index F_I of core sample is, respectively calculated and take correlation analysis with fracturing fracture geometry. According to the relationship between fracture geometry and fracability index, take judgment according to following standards: For $F_I \leq 0.25$, it is the Cannot form complex fractures. For $0.25 < F_I \leq 0.4$, the fracture complexity is ordinary. For $F_I > 0.4$, the fracture complexity is high.

Field application

In the reservoir with the same hydrocarbon-bearing conditions, the better the fracability, the more possible the hydraulic fracture network to be generated. A more complex fracture network meant bigger productivity. Fracability indexes of all wells of shale reservoir in the Dagang Oilfield through fracability evaluation model.

Conclusion

This paper proposes a fracability evaluation model that fits the actual conditions of on-site fracturing operation, which can provide guidance to the fracturing design of shale oil reservoir. In addition, other similar complex lithologies fractured shale oil reservoirs in China can also refer to this method to establish a suitable fracability evaluation model.

Nomenclature

D – fractal dimension, [–]
F_C – rock fracture complexity, [–]
E – young modulus, [MPa]
L – half-length of a hydraulic crack, [m]
P – minimum fluid pressure, [MPa]

Greek symbols

α – fracture angle, [°]
γ – crack surface energy, [MPam]
ν – Poisson's ratio, [–]
ψ – shear dilatancy angle, [°]

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