An integrated multi-scale fracability evaluation method for tight sandstone reservoir

C Y Peng\textsuperscript{1}, W J Liu\textsuperscript{2}, Z X Huang\textsuperscript{1}, Y X Cheng\textsuperscript{1}, B L Wu\textsuperscript{1}, and J T Deng\textsuperscript{2}

\textsuperscript{1} CNOOC research institute, Beijing 100028, China
\textsuperscript{2} State Key Laboratory of Petroleum Resources and Prospecting and College of Petroleum Engineering, China University of Petroleum, Beijing 102249, China

Abstract. Fracability evaluation of unconventional oil/gas reservoirs has become a general practice during the hydraulic fracturing job design to identify the best candidate pay zone. The brittleness of the reservoir rock was first used to characterize the capability of the reservoir rock to form a complex fracture network. Later, other factors like fracture toughness, in-situ stress, and natural fracture parameters were introduced in combination with brittleness to more comprehensively describe the fracability of the reservoir. However, most of the existing fracability evaluation has been performed for single wells. In contrast, the three-dimensional distribution of fracability within reservoirs was less pursued, though it might be beneficial for guiding the well placement.

This study developed an integrated multi-scale fracability evaluation method for tight sandstone reservoirs based on three-dimensional geomechanical analysis. Factors like brittleness, fracture toughness, in-situ stress contrast that influence the hydraulic fracture initiation and propagation at different scales were first identified and analyzed. Then methods of deriving these quantities from well logs and three-dimensional seismic data were summarized. Finally, an integrated index incorporating these quantities was defined to differentiate the so-called engineering sweet-spot zones favorable for stimulation. A typical application of this method is the integrated multi-scale fracability evaluation method applied to a tight sandstone reservoir located in China's south sea oil field, which demonstrated the effectiveness of the method. In addition, some implications for improving fracturing operations of tight sandstone reservoirs have been provided.

1. Introduction
The concept of fracability was originally proposed for shale reservoirs, and it is a quantitative indicator that intuitively describes whether or not the reservoir is favorable for fracturing. Early studies simply assumed that the more brittle the rock was, the easier it was to fracture. Therefore, only the brittleness index was used to measure the fracability of the reservoir rock. Different researchers put forward different definitions of brittleness. There are about a dozen brittleness calculation methods that are widely used, among which the two most common are: (1) The Mechanical Brittleness Index calculated by elastic parameters such as Young's modulus and Poisson ratio; and (2) The Mineral Brittleness Index defined by the percentage of brittle minerals.

For the Barnett shale in the Fort-Worth Basin in North America, Rickman et al. (2008) \cite{1} proposed that the higher the Young's modulus and Poisson's shale ratio, the more brittle the shale, the more favorable it is for fracturing. Jarvie et al. (2007) \cite{2} regarded quartz minerals as brittle minerals. They proposed that the ratio of brittle minerals to the total amount of minerals was defined as the brittleness index to measure the brittleness of shale. Jin et al. (2015) \cite{3} believe that the calculation of brittleness index with quartz as the only brittle mineral is incomplete, since feldspar, mica, and carbonate
minerals need to be considered. Li et al. (2012)\cite{4} proposed a method to comprehensively evaluate the brittleness of shale by integrating rock Young's modulus, Poisson ratio, and other elastic parameters with mineral components. For a long time, the brittleness index has been used as the only indicator to evaluate the fracability of the shale reservoir. This means that the evaluation method only considered the influence of factors at the scale of rock matrix on fracturing work and ignored factors at other scales such as fracture initiation and propagation.

With the continuous development of rock mechanics, it was gradually realized that other essential factors needed to be considered to evaluate the fracability of a reservoir more accurately. Yuan et al. (2013)\cite{5} argued that the elastic parameters alone were not enough to fully assess the reservoir's fracability. Site experience and laboratory experiments show that the hydraulic fracturing effect is quite different for some rocks with similar Young’s modulus and Poisson ratios. It was believed that the reason for this difference is the difference in fracture toughness. The fracture toughness characterizes the ability of a rock to resist cracks. This is an intrinsic property of the reservoir rocks and should be considered essential in fracture initiation and propagation. Jin et al. (2015)\cite{6} also argue that the brittleness index alone cannot fully characterize the fracturing of shale, and the energy consumed by rock failure during the fracturing process should also be considered. Therefore, they proposed that the critical energy release rate should be added to the fracability calculation. Tang et al. (2012)\cite{7} further suggested based on the original theory that natural fractures in the reservoir will reduce the tensile strength of the rock, making it favorable for the initiation and propagation of hydraulic fractures. In addition, the interconnection of hydraulic and natural fractures can form a more complex fracture network system, providing stronger conductivity. So, the propagation degree of natural fracture in rocks is also an important factor. Yuan et al. (2017)\cite{8} proposed adding the minimum horizontal in-situ stress as an influencing factor to the fracability evaluation. The fractures always propagate along the minimum horizontal in-situ stress trajectory, so the smaller it is, the more conducive it is to fracture initiation and propagation. Different kinds of new influencing factors have been proposed and applied, and a multi-factor comprehensive fracability evaluation method system for shale reservoirs has been gradually formed. In theory, the more comprehensive the factors considered, the more accurate evaluation results will be, but in actual applications, whether each factor needs to be considered depends on the reservoir's real situation.

At present, most of the fracability evaluation methods are aimed at shale oil and gas reservoirs. Sun et al. (2015)\cite{9} followed the fracability evaluation model of shale reservoirs and proposed a fracability evaluation method for tight sandstones that considered the brittleness index and fracture toughness. He et al. (2019)\cite{10} comprehensively considered eight influencing factors: mechanical brittleness, uniaxial compressive strength, mineral brittleness, cohesion, internal friction angle, natural cracks, fracture toughness, horizontal in-situ stress difference, and adopted the analytic hierarchy process to determine their respective weights. In general, the existing fracability evaluation models applied to other lithological reservoirs mostly followed the evaluation model of shale reservoirs. Still, improvements were made per the characteristics of the reservoirs.

2. Characterization of the reservoir rock

Samples of the reservoir rock from the LF Oilfield located in the South China Sea have been collected. In addition, a series of rock mechanics tests were carried out on the mechanical properties of these reservoir rocks.

2.1. SEM scanning experiment

To observe the internal conditions of the reservoir rock intuitively and confirm whether natural fractures exist in the reservoir rock or not, SEM scanning experiments were carried out on four samples (Figure 1). No natural fractures were found in the core through direct vision, and it is difficult to find obvious natural fractures under low magnification. However, some inter-crystalline micro-fractures can be observed under high magnification. The experimental result proved that there are seldom natural fractures within the target reservoir rock.
2.2. Fracture toughness test
This study performed the fracture toughness tests on 12 rock samples sourced from 4166.8 m underground depth. The rock sample is φ38 mm×10 mm, and a 1.1 cm straight seam is pre-made in the middle. To ensure the accuracy of the experimental results, the ratio of the half-fracture length to the radius of the rock sample (a/R) should not be greater than 0.3. The mode I and II fracture toughness of each rock sample were calculated and listed in Table 1. The mode I fracture toughness of the target reservoir rock is between 0.263–0.304 MPa·m$^{1/2}$, and the average value is 0.287 MPa·m$^{1/2}$; the mode II fracture toughness is between 0.417–0.489 MPa·m$^{1/2}$, and the average value is 0.459 MPa·m$^{1/2}$.

Table 1. Fracture toughness test results

| Depth /m | Thickness /mm | Diameter /mm | Seam length /mm | Load /KN | Included angle/° | Fracture toughness type | Fracture toughness (MPa·m$^{0.5}$) |
|----------|---------------|--------------|-----------------|----------|-----------------|------------------------|----------------------------------|
| 10.05    | 38.12         | 11.79        | 1.247           | 0        |                 | I                      | 0.282                            |
| 10.12    | 38.08         | 11.11        | 1.391           | 0        |                 | I                      | 0.304                            |
| 10.13    | 38.18         | 10.90        | 1.370           | 0        |                 | I                      | 0.295                            |
| 10.00    | 38.13         | 11.66        | 1.164           | 0        |                 | I                      | 0.263                            |
| 10.04    | 38.11         | 11.21        | 1.370           | 0        |                 | I                      | 0.302                            |
| 10.07    | 38.11         | 12.12        | 1.195           | 0        |                 | I                      | 0.274                            |
| 10.01    | 38.13         | 11.82        | 1.082           | 30       |                 | I                      | 0.446                            |
| 10.00    | 38.10         | 11.58        | 1.020           | 30       |                 | I                      | 0.417                            |
| 10.05    | 38.15         | 11.04        | 1.236           | 30       |                 | I                      | 0.488                            |
| 10.16    | 38.09         | 11.61        | 1.082           | 30       |                 | I                      | 0.436                            |
| 9.98     | 38.05         | 11.21        | 1.185           | 30       |                 | II                     | 0.476                            |
| 10.08    | 38.06         | 10.78        | 1.257           | 30       |                 | II                     | 0.489                            |

2.3. Tri-axial compression tests
In this experiment, the TAW-1000 experimental system is used to axially load the standard cylindrical-sized (ϕ 25 mm × 50 mm) rock sample under a confining pressure (tri-axial) until the rock is broken.

As a result, the mechanical properties, including Young’s modulus, the Poisson ratio, the internal friction angle, and the cohesion, were obtained and listed in Table 2.

**Table 2.** Tri-axial compressive strength test results

| Depth /m | Core No. | Density (g/cm³) | Confining pressure /MPa | Strength /MPa | Young’s Modulus /GPa | Poisson ratio | Cohesion /MPa | Internal Friction angle |
|----------|----------|-----------------|--------------------------|---------------|---------------------|---------------|---------------|------------------------|
| 4155.10  | 1        | 2.36            | 20                       | 213.13        | 30.37               | 0.28          |               |                        |
| 4166.80  | 2        | 2.37            | 30                       | 251.59        | 32.28               | 0.28          | 45.31         | 33.47                  |
| 4173.10  | 1        | 2.35            | 40                       | 262.32        | 34.37               | 0.24          |               |                        |
|          | 2        | 2.32            | 30                       | 209.35        | 31.10               | 0.26          |               |                        |
|          | 2        | 2.31            | 20                       | 187.99        | 30.86               | 0.28          |               |                        |
|          | 2        | 2.32            | 20                       | 209.35        | 31.10               | 0.26          | 41.01         | 31.10                  |
|          | 2        | 2.31            | 30                       | 223.10        | 31.93               | 0.22          | 45.08         | 31.00                  |

3. Establishment of an integrated multi-scale fracturing evaluation model suitable for low-permeability tight sandstone reservoirs

This study combines experiments and field data from the LF Oilfield to establish a fracability evaluation method suitable for tight sandstone reservoirs. Based on these data, suitable fracability evaluation factors are selected at the three scales: rock matrix, single fracture, and multi-fracture initiation and propagation. In addition, the following factors are equally considered: (1) Elastic parameters, fracture toughness, and brittleness; (2) Three-dimensional in-situ stress distribution in the target reservoir; (3) Single hydraulic fracture propagation and its controlling factors; (4) Interaction of multiple clusters of fractures and their propagation laws. Combining all the above, a multi-factor fracability evaluation method is established. Furthermore, relying on the on-site data of the LF Oilfield, 3D geological modeling, and 3D reservoir fracability evaluation were carried out, and the accuracy of the method was verified.

3.1. Rock matrix scale

Brittleness means the material undergoes fracture failure after only small deformation under external force. The brittle rock material experiences a small elastic deformation before being fractured and shows almost no plastic deformation. It is one of the most important properties that describe the fracability of reservoir rocks, and it is an influencing factor at the rock matrix scale. The impact of brittleness on fracturing is reflected in the fact that under the action of the fracturing fluid pumped in by high pressure, the reservoir rock will be fractured when the external force slightly exceeds its tensile strength. Furthermore, a generally accepted view is that reservoir rocks with strong plasticity have higher shale content and are prone to plastic deformation to form simple fractures during fracturing. However, brittle shale has a higher content of brittle minerals. Therefore, it is easier to form complex fracture networks during fracturing since the oil drainage area of the reservoir is larger.

Brittleness is one of the indispensable factors in fracability evaluation. The strength of rock brittleness is directly related to its composition. In mechanics, brittleness is reflected in Young’s modulus and Poisson ratio. The more brittle the rock, the greater Young’s modulus and Poisson ratio. Mechanical brittleness index, one of the two most commonly used brittleness indices, is defined as follow:

\[ B_n = \frac{E + \nu}{2} \]  

(1)
where, $B_m$ is Mechanical brittleness index: $\overline{E}, \nu$ are normalized Young's modulus and Poisson ratio, respectively.
The mineral brittleness index is defined as the percentage of brittle mineral content:

$$B_m = \frac{W_{bri}}{W_{tot}} \quad (2)$$

where, $B_m$ is Mineral brittleness index: $W_{bri}, W_{tot}$ are the content of brittle minerals and the total amount of minerals, respectively.

Research shows that although the definitions of the two brittleness indexes are different, they are essentially the same. Furthermore, the calculation results of the two definitions have a very strong positive correlation, so there is no need to reconsider. Therefore, this study uses the mechanical brittleness index to evaluate low-permeability tight sandstone reservoir fracability.

3.2. The scale of initiation and propagation of a single hydraulic fracture

3.2.1. Fracture toughness

Fracture toughness is the nature of the rock itself. It refers to the difficulty of initiation and propagation of fracture. We considered it as the influencing factor at the scale of the initiation and propagation of a single hydraulic fracture. The greater the fracture toughness of the rock, the more difficult it is fractured, and it is harder to form ideal fractures after hydraulic fracturing. In our evaluation method, mode I and mode II fracture toughness are taken into account.

The tight sandstone reservoir in LF Oilfield is deeply buried at a depth of 3900–4200 m. Indeed, the rock is subjected to heavy structural compression and has strong fracture toughness. Therefore, it is essential to use the appropriate empirical formulas for calculating fracture toughness based on rock tensile strength, and Young’s modulus:

$$K_{IC} = 0.131 + 0.047S$$

$$K_{HIC} = 0.343 + 0.0037E_s$$

(3)  (4)

The fracture toughness of rock samples can be measured through a fracture toughness test. However, due to the limited number of rock samples and the high cost of coring, the fracture toughness values measured from a few rock samples are only of the reference value and cannot be the compressible value of the entire reservoir’s fracability evaluation. Therefore, fracture toughness needs to be calculated based on sufficient on-site logging data for 3D evaluation.

3.2.2. Minimum horizontal in-situ stress

The initiation and propagation of fracture are closely related to the in-situ stress of the reservoir. Since the initiation of hydraulic fracture not only needs to overcome the fracture toughness of the rock but also need to overcome the in-situ stress on the initiation part. The traditional classical fracturing theory suggests that the hydraulic fracture in the deep well area is plane-symmetrical and double-winged, extending in the vertical direction of minimum in-situ stress. The minimum in-situ stress is another resistance that needs to be overcome. The smaller it is, the easier the fracture’s initiation and propagation will be.

Considering the characteristics of tight sandstone reservoirs, this study adopts the combined spring model as the in-situ stress calculation method:

$$\sigma_H = \frac{\mu_s (\sigma_z - \alpha P_0)}{1 - \mu_s} + \frac{\omega_2 \mu_s E_s}{1 - \mu_s} + \frac{\omega_1 E_s}{1 - \mu_s} + \alpha P_0$$

$$\sigma_h = \frac{\mu_s (\sigma_z - \alpha P_0)}{1 - \mu_s} + \frac{\omega_2 \mu_s E_s}{1 - \mu_s} + \frac{\omega_1 E_s}{1 - \mu_s} + \alpha P_0$$

(5)  (6)

where, $\mu_s, E_s$ are static Poisson ratio and Young's modulus, respectively; $\mu_d, E_d$ are dynamic Poisson ratio and Young's modulus, respectively; $\Delta t, \Delta t_p$ are transverse wave and longitudinal wave time difference, respectively; $P_p$ is the formation pore pressure; $\omega_1, \omega_2$ are Relaxation coefficient, obtained
by inversion of formation leakage experimental data, \( \omega_1 = 2.44 \times 10^{-4} \), \( \omega_2 = 7.07 \times 10^{-4} \); \( \alpha \) is the Biot coefficient; \( \sigma_z \) is overburden pressure; \( \rho_b \) is the pressure equivalent density of the overlying strata.

The model assumes that the reservoir is a homogeneous linear elastic object, taking into account the influence of Young's modulus on the in-situ stress, and more truly reflects the real underground situation.

3.3. The scale of initiation and propagation of multiple fractures

The ideal result of hydraulic fracturing is for it to form complex networks of fractures in the reservoir. In the propagation process, hydraulic fracture interacts with a natural fracture or other hydraulic fractures to create as large and complex fractures networks as possible to achieve the largest possible reservoir reformed volume, providing drainage channels with high conductivity for oil and gas. According to our study, the greater the difference between the maximum and minimum horizontal in-situ stress, the easier it is to form long, straight, simple hydraulic fractures. Due to the high-stress difference, it is difficult for hydraulic fractures to interact to form a complex fracture network. To quantify the horizontal in-situ stress difference, the horizontal in-situ stress difference coefficient is defined as follows:

\[
K_h = \frac{\sigma_H - \sigma_h}{\sigma_h}
\]  

(7)

where, \( K_h \) is the horizontal stress difference coefficient; \( \sigma_H, \sigma_h \) are the maximum and lowest horizontal in-situ stress, respectively.

As shown in Figure 2, in the process of hydraulic fracture propagation, simple long straight fractures can only pass through a few natural fractures and interact with them. When \( K_h \) is small, hydraulic fractures pass through and activate natural fractures, making them reopen new fractures. When the \( K_h \) is large, hydraulic fractures will pass through most natural fractures directly and cannot activate them. Only a few natural fractures with large intersection angles may be activated. Under this circumstance, it is difficult to form complex fractures networks in the reservoir.

![Figure 2. Interaction between hydraulic fractures and natural fractures under different K_h](image)

In summary, considering the scales of rock matrix, the initiation and propagation of single fracture and multiple fractures, 4 factors are taken into account to establish a new offshore tight and low-permeability sandstone reservoir fracability evaluation method:

\[
FI = B_n \times \frac{1}{0.5K_{IC} + 0.5K_{HC}} \times \frac{1}{\sigma_h} \times (1 - K_h)
\]  

(8)

4. Fracability evaluation of LF Oilfield

4.1. In-situ stress

Based on the above Kaiser in-situ stress test, it is preliminarily determined that the maximum and minimum horizontal in-situ stress equivalent density of the target reservoir are about 1.9 and 1.6 g/cm³, respectively, and the overlying formation pressure equivalent density is about 2.2 g/cm³. The
geological structure information shows that normal faults dominate the LF Oilfield, and the relationship of the in-situ stress should satisfy $\sigma_v > \sigma_H > \sigma_h$, which is consistent with the experimental results. Taking the experimental results as calibration, Petrel’s visage function was used to calculate the three-dimensional distribution of in-situ stress based on the established three-dimensional geological and attribute models. We compared it with the results calculated by the combined spring model (Figure 3), with excellent consistency. This confirms the high accuracy of the visage function.

4.2. Evaluation of fracability on single well scale and fracturing formation optimization

Based on the information of a typical exploratory well in LF Oilfield, the oil-bearing formation of the Wenchang Formation is screened according to the on-site logging interpretation result. Then, the fracability evaluation was carried out on the selected formations based on the logging data obtained from the exploratory well. Elastic parameters, fracture toughness, and in-situ stress of a single well were calculated. On this basis, the well’s profile is obtained. And the fracability index of the main oil-bearing zones could be easily estimated (Figure 4).

The evaluation results show that the average fracability index of the fourth part of the Wenchang Formation at the measuring depth of 3962.3–3989.2 m is 0.82. The average index of the upper section of the fifth part of the Wenchang Formation from 4015.7 to 4038.8 m is 0.79, the average value of the deeper section of the fifth part of Wenchang Formation from 4047 to 4101.2 m is 0.92. Therefore, the oil-bearing formation in the deeper fifth part of the Wenchang Formation is optimal.

4.3. Three-dimensional fracability evaluation and screening of fracturing engineering sweet-spots

Based on the three-dimensional reservoir geological model developed with the Petrel software, the on-site logging data of two typical wells pass through the three-dimensional geological area, obtaining the
3D distribution of logging data by coarse logging curve and 3D inter-well interpolation. Then, calculations were made to obtain the three-dimensional distribution of the static mechanical parameters and fracture toughness of the reservoir. Three-dimensional evaluations were further performed to examine the reservoir rock's brittleness. The results show that the area around the typical well and southwest areas are brittle areas.

![Figure 5. Three-dimensional distribution of static mechanical parameters](image)

**Figure 5.** Three-dimensional distribution of static mechanical parameters

Based on the completed three-dimensional distribution of static mechanical parameters and fracture toughness, combined with the three-dimensional in-situ stress calculation results, comprehensive calculations were carried out to conduct a complete fracability evaluation of the established geological area and provide a basis for identifying engineering sweet-spots of hydraulic fracturing engineering.

![Figure 6. Three-dimensional distribution of brittleness index](image)

**Figure 6.** Three-dimensional distribution of brittleness index

5. **Verification of fracability evaluation method**

Since LF Oilfield is a newly developing offshore tight sandstone oilfield, complete productivity and seismic data are lacking. Therefore, it is rather difficult to verify the applicability of our fracability evaluation method directly through the field data or on-site fracturing effect. Field data and productivity data of a typical tight gas sandstone reservoir were used to establish a productivity index according to the physical properties of the reservoir and the fracturing process parameters. To achieve
verification, fracability evaluation of the tight gas sandstone reservoir was completed, and we established the relationship with productivity indexes.

![Figure 8. Fracability - Productivity index relationship (LX Gas field)](image)

The results show that, on the whole, the productivity index of a single well with a higher fracability index is relatively higher. There is a good positive correlation between fracability and production after fracturing, which indirectly proves that our fracability evaluation method has good applicability to tight sandstone reservoirs.

6. Conclusions

This study created an integrated multi-scale fracability evaluation method for tight sandstone reservoir, based on the basic theoretical research, rock sample experiment, and logging data taken from LF Oilfield. After verification, it was proved that it has a good guiding significance for the fracturing of tight sandstone reservoirs.

1) The integrated multi-scale fracability evaluation method’s establishment comprehensively considers four different influencing factors at the three major scales: rock matrix, single hydraulic fracture, and multiple/clustered hydraulic fractures initiation and propagation. Thus, it is a comprehensive and easy-to-operate evaluation method.

2) When the mechanical experiment results and logging data are complete, the evaluation method can be used with Petrel software to perform vertical layer selection and three-dimensional fracturing evaluation of any tight sandstone reservoir. It has a wide range of applications, and the result of engineering sweet-spots selection is more intuitive.

3) This application of fracability evaluation can achieve reasonably good evaluation results when there are few exploratory wells in the applied area and a lack of sufficient logging data. Therefore, it is also applicable to oilfields in the early stages of development.

7. References

[1] Rickman R, Mullen M, Petre E, et al. 2008 A practical use of shale petro-physics for stimulation design optimization: all shale plays are not clones of the Barnett Shale. J.SPE 15258.

[2] D M Jarvie, R J Hill, T E Ruble, et al. 2007 Unconventional shale-gas systems: The Mississipian Barnett Shale of north-central Texas as one model for thermogenic shale-gas assessment. A APG Bulletin 475-499.

[3] X C Jin, S N Roegiers, J C Roegiers, et al. 2015 An Integrated Petrophysics and Geomechanics Approach for Fracability Evaluation in Shale Reservoirs. J.SPE 518-526.

[4] Q H Li, M Chen, Y Jin, B Hou, J Z Zhang. 2012 Rock mechanical properties and brittleness evaluation of shale gas reservoirs. Petroleum Drilling Technology 17-22.

[5] J L Yuan, J G Deng, D Y Zhang, D H Li, W Yan, C G Chen, L J Cheng and Z J Chen. 2013 Evaluation technology for fracturing of shale gas reservoirs. Acta Petrolei Sinica 523-527.
[6] Jin X. et al. 2015 An integrated petrophysics and geomechanics approach for fracability evaluation in shale reservoirs. J.SPE 518-526.

[7] Y Tang, Y Xing, L Z Li, B H Zhang, and S X Jiang. 2012 Influencing factors and evaluation methods for fracturing of shale reservoirs. Earth Science Frontiers 356-363.

[8] J L Yuan, J L Zhou, S J Liu, et al. 2017 An improved fracability-evaluation method for shale reservoirs based on new fracture toughness-prediction models. J.SPE 1, 704-1, 713.

[9] J M Sun, Z L Han, R B Qin, J Y Zhan. Logging evaluation method for fracturing of tight gas reservoirs. Acta Petrolei Sinica 74-80.

[10] H Rui, Z Z Yang, X G Li, Z L Li, Z Y Liu and F Chen. 2019 A comprehensive approach for fracability evaluation in naturally fractured sandstone reservoirs based on analytical hierarchy process method. Energy Science & Engineering 7(2).

[11] X T Zhang, X D Wang, Y Shu, S F Zhang, X M Que, Q H She, and Y F Wang. 2017 Geological characteristics and formation conditions of large and medium-sized oil fields in LF Sag, Pearl River Mouth Basin. Journal of Central South University 2979-2989.

[12] L H Jiang. 2016 A high-efficiency acid suitable for deflagration fracturing acidification in LF Oilfield. Petrochemical Industry Application 5-8.