Application of Discrete Fracture Network Model in the Simulation of Massive Fracturing in Tight Oil Reservoir

He Chun Ming1, Shi San Zhi2, Zhanghui3, Li Shuai1, Chen Jin2, Cheng Ning2, Duanguifu1

1 PetroChina Research Institute of Petroleum Exploration & Development, Langfang city, Hebei Province, 065007, China
2 Xinjiang Oilfield Company, PetroChina, Kelamayi city, Xinjiang Province, 834000, China
3 Huabei Oilfield Company, Petro China, Renqiu city, Hebei Province, 062552, China
E-mail: hcm8898533@163.com

Abstract: Massive fracturing technology can form a complex fracture network and a large drainage area by multi-stage/multi-cluster perforation and injection of low viscosity fluids such as slickwater. The traditional bi-wing planar model is not applicable in the simulation of massive fracturing, and a new network model is needed. The pseudo-three-dimension (P3D) Discrete Fracture Network (DFN) model are based on self-similar solution methodology, and the fracture characteristics are then calculated numerically. We performed a comparison between DFN model and Cluster Fracture model through the integration of rock mechanics, well logging and micro seismic detection technology. After the mini-fracture analysis and closure analysis, parameters like instantaneous shut-in pressure (ISIP), closure pressure and reservoir permeability were obtained. Based on these parameters, pressure history match and SRV match were performed, the result shows that DFN model works better than the Cluster Fracture model in the matching. The research proves the feasibility of DFN model in the simulation of massive fracturing in tight oil reservoirs.

1. Introduction
The exploration and development of the tight oil have been a hot fields in recent years. Multiple hydraulically fractured horizontal wells (MHFHW) can form a bigger stimulate reservoir volumes (SRV), and enhance the production and ultimate recovery and has been a key technology in the development of tight oil.

The research of massive fracturing has been a long process. Davidson[1] pointed out that formation with natural fractures developed is easier to form secondary fractures when hydraulic fracturing. Weng[2] believed that the increase of fracture net pressure will result in the veer of fractures, and form multi-fractures in the end. King[3] found the fracture networks after hydraulic fracturing in Barnett shale gas reservoirs via microseism. Warpinski[4] divided the fractures into planar, planar-decoupled, complex planar and fracture networks and divided the proppant sedimentation into evenly distributed and concentrated in a dominant fracture. Yeager[5] confirmed the fracture closing pressure, net pressure, liquid efficiency and reservoir permeability via mini-fracturing analysis. Jacot[6] synthesized well logging, mini-fracturing, and microseism in Marcellus and Eagle Ford shale gas reservoir. Meyer[7] build a DFN model based on Warren Root model and form the discrete three-dimensional...
model. In China, some scholars summarized the basic connotation, design procedures, but they didn’t simulate the massive fracturing through DFN model. In this paper, we take the Changqing oil field as an example, combine the microseism and the mini-fracturing, contrast the DFN model and the cluster model, and prove the applicability of DFN model in tight oil reservoirs.

2. Geology and fracturing situation

2.1 Geology situation

An 83 well block located in Ordos Basin in Shanxi province, the terrain of this area is very complex. Specific location of An 83 well block, Stratigraphic section of this block is shown in Figure 1.

Fig.1 Stratigraphic section of An83 Block

Generally speaking, high fracturing fluid inject rate and large scale fracturing is available for the formation of network. But the reservoir characteristics also affect the generating of fracture networks including natural fracture, reservoir stratification, fissure distribution, stress condition and brittleness. We contrast the Chang7 tight oilfield in China and Barnett shale gas in table1, and we get the conclusion that Chang7 tight oilfield is suitable for massive fracturing.

| Oilfield           | Depth /m | Thickness /m | Lithology | Natural fracture | Brittleness /GPa | Porosity /% | Permeability / (10^-3 μm²) | Pressure gradient /(MPa cm⁻¹) |
|--------------------|----------|--------------|-----------|------------------|------------------|-------------|-----------------------------|------------------------------|
| Chang7 tight oil field | 2 500    | 20           | sandstone | comparable development | 10~20           | 8~12        | 0.1~1.0                   | 0.85                         |
| Barnett shale gas  | 1 581~2 590 | 30~182       | mudstone  | development      | > 60            | 4~5         | < 0.000 1                | 0.97                         |

2.2 Fracturing situation

Well A is located in Chang7 formation. It’s total depth is 2528m, average porosity is 8.18%, average permeability is 0.26×10⁻³ μm². Fracturing fluid is injected both in tubing and casing to get a high fracture net pressure. This fracturing method makes the natural fracture open and connected with the hydraulic fracture to get a larger SRV volume. The fracturing fluid is slickwater to reduce the formation damage, and obtain a higher oil output. The fracturing rate is 10 m³/min, prepad fluid is 88 m³, sand-laden fluid is 450 m³, the total sand is 91.3t, the proppant is ceramsite of 40/70 and 20/40. Figure 2 shows the microseism detection of well A.
3. Mini-fracturing analyses
To get the parameters for fracturing design, mini-fracturing analysis is needed. Closure stress, fluid leak-off coefficient, reservoir pressure and reservoir permeability can be obtained by mini-fracture analysis.

3.1 Step rate analysis
Step rate analysis is used to determine the extension pressure of the fracture, the upper bound for the minimum horizontal stress and closure pressure. When the formation is cracked, fluid is pumped at an increasing flow rates in a stair-step fashion. In the ideal condition, each flow rate should maintained until a stabilized pressure is achieved. Finally, the fracture extension pressure is 23.0 MPa.

3.2 Horner analysis
Horner analysis is used to determine if pseudo-radial flow reached during pressure decline. If a semi-log straight line is observed and the line can be extrapolated to a reasonable value of reservoir pressure, radial or pseudo-radial flow may affects the decline behavior. This suggests that the fracture has already closed. The Horner plot provides a lower bound of the minimum horizontal stress or closure pressure.

Figure 2 is a graphical plot of Horner analysis. Normally, plotting pressure versus Horner time ($\log(\frac{t}{t-t_p})$) will help to identify the onset of pseudo radial flow. This time function is typically defined as $\log(\frac{t}{t-t_p})$, where $t_p$ is the pump time, $(t-t_p)$ is the shut-in time. The Horner plot provides a lower bound of closure pressure. As shown in Figure 3, the initial estimate of pore pressure ($p^*$) is 27.2 MPa.

3.3 Regression Analysis
The purpose of regression analysis is to get parameters such as closure pressure, near wellbore effects, fracture efficiency, and leak off coefficients. Nolte derived the relationship between pressure drop and dimensionless time from conservation of mass and volume balance. $G$ function and instantaneous shut-in pressure of the fracture is expressed as formula (1).
The limiting G-Function solutions for \( \alpha_s = 0, \alpha_s = 1/2, \alpha_s = 1 \) are

\[
G(0, 0, t_D) = \frac{8}{\pi(t_D^{1/2} - 1)}
\]  

(2)

\[
G(\frac{1}{2}, 0, t_D) = \frac{4}{\pi(t_D\arcsin t_D)^{1/2}} + (t_D - 1)^{1/2} - \frac{\pi}{2}
\]  

(3)

\[
G(1, 0, t_D) = \frac{16}{3\pi(t_D^{3/2} - (t_D - 1)^{3/2} - 1)}
\]  

(4)

where the dimensionless time is given by \( t_0 = t/t_p \).

Figure 4 and Figure 5 is Nolte G function plot and square root function plot, respectively. Line 1A-1B and 2A-2B are tangent of the curve, and their intersection is \( t_c \). Intersection of 1A-1B and vertical coordinates (when Nolte time is zero) is ISIP. These two kinds of analysis method are compared and make differences in calculating the reservoir parameters.

![Fig.4 Curve of Nolte G analysis method](image)

![Fig.5 Curve of square root function analysis method](image)

### Table 2 Comparison between Nolte G method and square root function method

| Analysis method     | Closure stress /MPa | Closure time /min | Net pressure /MPa | Pressure gradient / (MPa·m⁻¹) | Liquid efficiency /% |
|---------------------|---------------------|-------------------|-------------------|-------------------------------|----------------------|
| Nolte G function    | 28.8                | 28.3              | 0.99              | 11.6                          | 0.151                |
| Square root function| 28.3                | 35.2              | 1.6               | 11.4                          | 0.277                |

### 3.4 After closure analysis

The purpose of the after closure analysis is to determine the reservoir permeability and pressure from the pressure response during the late time period. Nolte (1997) derived an after closure time function \( F_R(t, t_c) \) by substituting an apparent closure time, \( \chi t_c \), \( (\chi = 16/\pi^2) \) into a Horner type time function. The resulting Nolte pressure response is:

\[
p_t - p_i = m_k F_R(t, t_c)
\]  

(5)
where \( F_R(t, t_c) = \frac{1}{4} \ln(1 + \chi t_c / \Delta t), m_R = \frac{\mu}{\pi K h} \frac{V}{t_c} = \frac{\pi \mu}{16 K h} \frac{V}{t_c} \) and \( K = \frac{\pi \mu}{16 m_h h} \frac{V}{t_c} \).

The equation \( p = p^* + F_R \frac{dp}{dF_R} \) is used to identify the radial flow and we can get the reservoir permeability by pressure data, the intercept \( p^* \) (reservoir pressure) and the slope \( (m_R = \frac{dp}{dF_R}) \). The reservoir pressure is 17.04 MPa while the reservoir permeability is \( 0.652 \times 10^{-3} \mu m^2 \).

### 3.5 Net pressure matching

The fracture generated by the traditional hydraulic fracturing is bee-wings, while when the reservoir rock with high brittleness and developed natural fractures, the massive fracturing can lead the extension of the natural fractures, connecting natural fractures and artificial fractures to form a fracture network. This is also verified by the microseism test data. Under these circumstances, the bee-wings model is not in application and new fracturing model is needed. We contrast the DFN model and cluster model on the basis of net pressure match and fracture network match.

#### 3.5.1 DFN model

The pseudo-dimension DFN model is firstly used in the stimulation of fracture cluster and fracture network in shale gas and coaled methane. The fundamental DFN mass and momentum conservation equations are based on a self-similar solution methodology. The formulation utilizes a pseudo-three-dimensional ellipsoidal approach. The major assumptions are as follows.

1. The dominate fracture or main fracture is in the \( x-z \) plane and propagates perpendicular to the minimum horizontal stress, \( \sigma_3 \). The \( y-z \) and \( x-y \) planes propagate perpendicular to \( \sigma_2 \) and \( \sigma_1 \), respectively.

2. The discrete fracture network may be composed of secondary fractures in all three principle planes. The spacing in the \( x-z \), \( y-z \), and \( x-y \) planes are \( \Delta y \), \( \Delta x \), and \( \Delta z \), respectively.

3. Fracture will only propagate in the \( y-z \) and \( x-y \) planes if the fracture pressure is greater than the corresponding minimum horizontal stress in that plane.

4. The numerical solution will be based on ellipsoidal self-similar type equations. That is the fractures stimulated reservoir volume will be ellipsoidal as will the geometric distributions. The width and height profiles are however calculated from the governing p3D pressure-width-height relationships.

5. Fracture interaction for stiffness and fluid loss is considered.

Through the net pressure match and fracture network match we get the parameters like closure stress gradient, reservoir permeability and fluid leak-off coefficient. The reservoir permeability got by the net pressure is \( 0.732 \times 10^{-3} \mu m^2 \), which is similar with the after closure analysis. At last we get the parameters of fluid leak-off coefficient is \( 0.015 \text{ cm/min}^{0.5} \). Figure 6 shows the fracture network matching and the 3D view of the network and Table 3 is the comparison between DFN model and microseism detection data.

![Fracture network matching](image)
3.5.2 Cluster fractures
Cluster fractures allow fractures to propagate in all three principle planes. Cluster fractures are assumed to be self similar, but can be of finite extent. The main fractures and the secondary fractures interact each other and extend in the same secondary fractures. The fracturing fluids concentrate in the main fractures, and will generate a greater fracture network. In this model the number of fractures, fracturing spacing, fracture aperture ratios, and aspect ratio can be defined.

We do the research of net pressure match and fracture network match with this model. Figure 7 shows the network match and cluster fractures 3D view map. Table 4 is the comparison between cluster fracture and microseism detection data.

![Fracture network match](image)

![3D Fracture network view](image)

**Table 3 Parameters match of DFN model**

| Category         | SRV Length/m | SRV Width/m | SRV Height/m |
|------------------|--------------|-------------|--------------|
| DFN modeling     | 380          | 180         | 32           |
| Microseism detection | 400         | 170         | 40           |

**Table 4 Parameters match of cluster model**

| Category                | SRV Length/m | SRV Width/m | SRV Height/m |
|-------------------------|--------------|-------------|--------------|
| Cluster fracture model  | 490          | 200         | 27           |
| Microseism detect data  | 400          | 170         | 40           |
3.6 Summary
From table 3 and Table 4, we can get the conclusion: in the DFN model, the secondary fractures connected easier, and extend greater than the cluster model in the height. So the DFN model is better in the matching of net pressure and fracture network, and DFN model is feasibility in the modeling of massive fracturing.

4. Conclusion
(1) Massive fracturing lead larger stimulates reservoir volume, the traditional bee-wing model is not in use, and the discrete fracture network model is a better one.

(2) Depend on the mini-fracturing analysis we get the reservoir data: fracture extend pressure is 23MPa, closure stress is 28.6 MPa, closure stress gradient is 11.5 kPa/m, the ISIP is 29.9 MPa, liquid efficiency is 19.2%, and the reservoir permeability is 0.652×10⁻³ μm².

(3) From the net pressure match and fracture network match of the DFN model and cluster fracture model we can see that DFN model is much fitting in the match with microseism detected data, and the SRV length is 380 m, SRV width is 180 m and the SRV height is 32 m.

Acknowledgements
This work is supported by the National Science and Technology Major Project. The paper is supported by the National Science and Technology Major Projects of China (NO. 2017ZX05070) and (NO. 2017ZX05023).

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