A multi-scale and multi-medium numerical model of a multi-fractured horizontal well in tight oil reservoir of Daqing oil field

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Abstract. The macroscopic geological conditions and microscopic pore characteristics of tight oil reservoirs are always complex. A multi-medium and multi-scale numerical model which can best embody tight oil reservoir features for a multi–fractured horizontal well (MFHW) is hard to establish. Without a reasonable numerical model, the evaluation and adjustment of a MFHW in a tight oil reservoir are difficult to fulfil. Based on the experiment results, geological data and construction parameters of the Pu34 well area, this paper establishes a multi-scale and multi-medium numerical model of a MFHW, Well X, in Daqing Oil Field and simulates the development effect of Well X after refracturing measurement. The results show that three types of reservoirs and four kinds of pore media exist in the Pu34 area. The history match shows the numerical model works well. By using this numerical model, the Well X, after re-fracturing, would perform better than without re-fracturing in the early stage of production period, and it also increases the cumulative oil production by 223t after production of 10 years. In economy regard, it has faster oil recovery rate which is helpful for company to recover the investment cost of this well.

1. Introduction
Pu34 well area is located at Putaohua anticline shaft in the central depression of the Songliao Basin [1]. A number of normal faults developed in the north-south direction. Tight oil reservoir is primarily found in Fuyu Reservoir and deposited in a delta-front sedimentary environment [2]. The average effective porosity of Fuyu Reservoir is 12.6% and permeability is 1.3mD. The lithology of the reservoir is dominated by siltstone, with some exception of calcareous and argillaceous siltstones. Fuyu Reservoir has many oil layers longitudinally that are small in scale and poor in transverse continuity. Macroscopically, it is characterized by poor physical properties and scattered distribution features of tight oil reservoirs.
At present, most of numerical models for tight oil reservoirs are still relatively continuous and even homogeneous which excludes the characteristics of macro and micro heterogeneity and differences between various media (reservoir matrix, fractures). Large differences exist in compositions, quantity distributions and flow behavior in different media. Therefore, the numerical model of tight oil reservoirs is supposed to embrace various media, which are different-scale pores from nano-scale to micro-scale usually also involving different-scale fracture media. In the case of multi-fractured horizontal well which is commonly used in the development of tight oil reservoirs, hydraulic fracturing usually also forms a complex hydraulic fracture network. All these features make the theory and technology of conventional reservoir numerical modeling not applicable here. Taking a multi fractured horizontal well in Pu34 well area as an example, the paper innovatively built a discrete multi-scale multiple media reservoir model.

2. Establishment of numerical model

2.1 The establishment of pore medium model

The tight oil reservoir matrix has strong heterogeneity. Different types of reservoir matrix are composed of quantity assemblage of different-size pore. Oil flows through pores of different sizes present different seepage mechanisms and flow patterns and so coupling seepage and development performance would be affected accordingly [3]. According to the sedimentary background and diagenesis law, every type of reservoir possesses a different quantity composition of different size pore. Therefore, classifying reservoirs based on microscopic pore characteristic is the foundation for establishing a model closer to reality.

![Figure 1. Capillary pressure curve of each type reservoir in Pu34 well area](image1)

![Figure 2. Mercury saturation increments in different pore-throat radius of each type reservoir in Pu34 well area](image2)

The lower limit of reservoir physical properties is 8% of porosity and 0.2 mD of permeability by oil occurrence method [4]. Tight oil reservoirs in well area can be classified into three types by statistical data of capillary pressure curve, as shown in Figure 1, obtained from core test. The features of type I are that the displacement pressure is about 0.3 MPa; the maximum pore-throat radius is 3μm; the median pore-throat radius is 0.9μm; the pore-throat radius is concentrated in 0.1-1 μm; the platform part of the curve is short and which means sorting is poor; The pore-throat distribution is characterized by a single peak, with the main peak at about 0.5μm. Accordingly minimum calculated permeability is 1.3 mD and porosity is 12% calculated by pore-permeability correlation. Due to the limited text body, the other two types will not be repeated here.

Based on reservoir classification criteria and results of mercury injection experiment, as shown in Figure 2, pore volume percentages of different sizes can be obtained for each type of reservoir. Different
size pores are further classified into four pore media as modeling unit based on the classification criteria that pore-throat radius less than 0.025μm is nano pore, pore-throat radius between 0.025 to 0.1μm is micro-nano pore, pore-throat radius between 0.1 to 1μm is micro pore and pore-throat radius more than 1μm is small pore. The results of classification are shown in Table 1. According to conservation of pore volume, porosity of four pore media that nano pore is 2%, micro-nano pore is 8%, micro pore is 14% and small pore is 20% can be calculated. In this way we can also calculate other physical properties of different-scale pore media based on property correlations.

| Reservoir type | Percentage of small pore (%) | Percentage of micro pore (%) | Percentage of micro-nano pore (%) | Percentage of nano pore (%) | Bulk average porosity (%) |
|---------------|-----------------------------|-----------------------------|----------------------------------|---------------------------|--------------------------|
| Type I        | 36                          | 46                          | 11                               | 9                         | 13.86                    |
| Type II       | 18                          | 32                          | 36                               | 14                        | 11.26                    |
| Type III      | 15                          | 16                          | 46                               | 23                        | 9.3                      |
| Non-reservoir | 2                           | 0                           | 8                                | 92                        | 2.6                      |

The microscopic basic analysis part of pore medium modeling has been completed through above work. The next step is to find the pore medium distribution law in plane. Based on the basic geological background, sedimentary environment and the porosity modeling result [5], as shown in Figure 3, and in combination with the classification result of reservoir type of Well X based on logging interpretation results [6-7], the plane distribution of different type reservoirs can be obtained which is shown in Figure 4. The type I reservoir develops in underwater distributary channel micro-facies. The type II reservoir develops in mouth bar and Type III in sheeted sand. In each type reservoir, we can distribute a certain quantity of each scale pore medium with the above quantity percentage results. This paper regards the different scale pore media are in a random plane distribution.

2.2 The establishment of fracture medium model
Natural fractures are commonly developed in tight oil reservoirs; and hydraulic fracturing networks are formed in the process of reservoir stimulation. These fracturing networks are the necessary conditions for tight oil reservoirs to obtain industrial oil flow. The direction of maximum horizontal principal stress is between N80.2°E to N92.5°E through core differential strain experiments.

2.2.1 The establishment of natural fractures model. There are few definite data such as core, thin section or imaging logging for natural fracture research in this area. Therefore, this paper mainly uses non-Poisson model spatial variable probability method to characterize the influence of faults on the distribution density of natural fractures. We define fractures with length of more than 10m as large scale
natural fractures, fractures with length between 1m to 10m as medium scale fractures and fractures with length less than 1m to 10m as small scale fractures [8-9].

2.2.2 The establishment of hydraulic fractures. Well X was stimulated by network volume fracturing and its designed cluster spacing is 100m, the whole well was fractured into 5 stages and 9 clusters. Table 2 shows the geometric parameters of clusters. Through fracture monitoring, we can get the size information of hydraulic fracture. According to fracturing construction data and monitoring data, we can simulate the fracture shape considering geostress condition.

| Monitoring results | Cluster | Left-side fracture length (m) | Right-side fracture length (m) | Width of cluster | Height of fracture (m) | Fracture strike |
|--------------------|---------|-------------------------------|-------------------------------|-----------------|-----------------------|----------------|
| Stage 1            | Cluster 1 | 167                           | 115                           | 56              | 25                    | N76°E          |
|                     | Cluster 2 | 205                           | 145                           | 51              | 31                    | N74°E          |
| Stage 2            | Cluster 1 | 163                           | 69                            | 66              | 35                    | N72°E          |
|                     | Cluster 2 | 264                           | 102                           | 43              | 33                    | N74°E          |
| Stage 3            | Cluster 1 | 306                           | 145                           | 68              | 34                    | N88°E          |
|                     | Cluster 2 | 312                           | 167                           | 71              | 40                    | N89°E          |
| Stage 4            | Cluster 1 | 186                           | 193                           | 54              | 23                    | N72°E          |
|                     | Cluster 2 | 272                           | 145                           | 55              | 25                    | N73°E          |
| Stage 5            | Cluster 1 | 146                           | 78                            | 58              | 16                    | N78°E          |

2.3 The establishment of integrated numerical model
The drilling direction of Well X is NNW, and the horizontal section is 840m. It is located at the relatively flat terrain where a normal fault lies on the left side, so the model boundary is not total rectangle.

Figure 5. Numerical model with pore media, natural and hydraulic fracture media of Well X
Figure 6. Refined numerical model by different grids

Considering horizontal section length, drilling direction and boundary effect, we have established a 1.3 km long and 900m wide numerical model along Well X. The mesh sizes of X, Y and Z directions are 20m, 20m and 3m, respectively. Figure 5 shows different pore medium are spread in the model. Based on the related experiment data, the relative permeability curves and dynamic equations of oil of different size pore media are assigned for each size pore. According to the results of seismic monitoring and fracturing shape simulation, hydraulic fracture model is established. Wellbore are refined with
quadrilateral grids, fractures with triangular unstructured grids, and matrix with Pebi grids, as shown in Figure 6.

3. Numerical model history match

History match is a very important process in the research of reservoir numerical simulation. It can verify the validity of a numerical model and adjust reservoir static data with the feedback result. Figure 7 shows the simulation pressure has a good match with the real pressure data. Therefore, we can regard our numerical model is believed to has good ability to reflect real tight oil reservoirs and to give some further measurement suggestion for Well X.

![Figure 7. Borehole pressure fitting curve of simulation result of Well X](image)

4. Simulation of refracturing effect for Well X

Through the understanding of Well X, we can know the original spacing of clusters is a little big, so we would like to suggest the Well X should be re-fractured to make the cluster spacing 50m. Therefore, 8 more fractures were added in the numerical model. The pressure distribution results of two models at the same time of 300 days after production are shown in the Figure 8 and Figure 9. It can be seen that the pressure of model without re-fracturing has a slower decreasing rate; and compared with the refractured one, the area between hydraulic fractures has not been swept until then. Moreover, the model refractured has a broader sweep volume then. If we look at the cumulative production curve shown in Figure 10, we can conclude that after refracturing, the model has a better production performance than without refracturing in the early stage of the simulation process, and it increases the cumulative oil production by 223t and it has faster oil recovery rate.

![Figure 8. The pressure distribution of Well X at the time of 300 days after production without re-fracturing](image)

![Figure 9. The pressure distribution of Well X at the time of 300 days after production with re-fracturing](image)
Figure 10. The simulated cumulative production curve of refractured numerical model and without refracturing

5. Conclusion
(1) On the basis of high-pressure mercury injection experiments, sedimentary background and geostatistics method, the composition characteristics of pore medium, reservoir classification criteria and plane distribution of each type reservoir are obtained. The distribution characteristics, geometric parameters and physical properties of fracture media are also obtained.

(2) According to the related parameters for modeling, a 20m×20m×3m integrated numerical model of Well X which are composed of pore medium, natural fracture medium and hydraulic fracture medium is established by self–developed software. The model is able to reflect tight oil reservoir characteristics.

(3) If the Well X were re-fractured, it would perform better than without re-fracturing in the early stage of production period. It also increases the cumulative oil production by 223t after production of 10 years. It has faster oil recovery rate which is helpful for oil field to recover the investment cost of this well.

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