Application of wellbore strengthening drilling fluid technology in Lingshui gas field

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Abstract. Fractured reservoir is developed in Lingshui gas field and the problem of lost circulation is prominent. To improve the pressure bearing capacity of fractured formation, the wellbore strengthening technology was applied in this block. The fracture width of Lingshui gas field was predicted with finite element method, which considered the effect of wellbore pressure, in-situ stress, seepage fluid and pore pressure. The simulation results showed that the fracture width of Lingshui block ranged from 0 to 464 μm. Based on the prediction results of fracture width, the particle size distribution of lost circulation material (LCM) was selected with dynamic fracture width testing device. The results indicated that the D50 rule has the best sealing efficiency. The optimized LCM formula had better compatibility performance with water-based drilling fluid. The sealing results illustrated that invasion depth of seepage loss was smaller than 0.3 cm and the pressure bearing capacity of fracture reached to 17 MPa.

1. Introduction

The geological conditions of Lingshui gas field are complex. The micro fractures are developed in the reservoir section. The existence of abnormal high pressure section leads to narrow safety mud weight window. It is easy to occur fractured leakage. The empirical plugging method is mainly used in lost circulation curing technology, which has low plugging success rate and leads to the frequent accidents of lost circulation. Thus, the lost circulation has a serious impact on the safe and efficient development of Lingshui gas field.

With the development of lost circulation preventing and curing technology, the wellbore strengthening has become an important method to broaden safety mud weight window, which can effectively improve the pressure bearing capacity through tight sealing. The wellbore strengthening theory mainly consists of stress cage theory, fracture closure stress theory and fracture extension resistance theory [1]. Alberty and McLean firstly proposed stress cage model, which was successfully applied to drilling operations in the Gulf of Mexico by Halliburton and increased the fracture pressure [2]. Dupriest described the fracture closure stress theory, which was applied to high permeability formation by Exxon and significantly improved the pressure bearing capacity [3]. van Oort et al. proposed fracture extension resistance theory, which has been applied in deep water area of Gulf of Mexico by M-I SWACO and the lost circulation accident was reduced by 80% [4].

The effect of wellbore strengthening on Lingshui gas field was investigated to broaden the safe mud weight window of deep water well. Firstly, the fracture aperture was calculated according to the
rheological parameters of drilling fluid and the mechanical properties of rock. Based on the predicted fracture width, the optimization experiment of particle size distribution of LCM was carried out by using the particle size matching criterion. The dynamic fracture width simulation device was used in sealing experiment. The research is of guiding significance for the optimization of curing lost circulation operation in Lingshui gas field.

2. Prediction of fracture width

2.1. Model construction

Based on the assumption of plane strain model, the wellbore section is taken as the simulation object. The basic shape and stress of the model are shown as figure 1.

![Figure 1. Diagram of physical model of lost circulation.](image)

It is assumed that the rock is a homogeneous porous elastic medium with completely saturated pores. The model is mainly affected by the wellbore pressure, maximum horizontal stress and minimum horizontal stress. The pressure in the fracture is equal to the wellbore pressure during the lost circulation process.

According to the principle of symmetry, the upper and left boundaries of the model are symmetric boundary conditions. The right and the lower boundaries of the model have the horizontal principal stresses and the pore pressure boundary conditions. The initial displacement of the model is zero and the initial pressure of whole domain is pore pressure. The simulation is completed in two steps. The first step is to balance the in-situ stress and the second step is to simulate the leakage process.

| Parameter            | Value | Unit  |
|----------------------|-------|-------|
| Maximum horizontal stress | 62.9  | MPa   |
| Minimum horizontal stress | 53.7  | MPa   |
| Pore pressure        | 40.8  | MPa   |
| Young’s modulus      | 7.5   | GPa   |
| Possion’s ratio      | 0.23  | Dimensionless |
| Void ratio           | 0.25  | Dimensionless |
| Permeability         | 15    | mD    |
| Leak off rate        | 20    | m³/h  |
2.2. **Prediction of fracture width**

According to the finite element method, the fracture opening under the condition of lost circulation can be calculated as follows.

![Figure 2. Simulation results of fracture width.](image)

As shown in figure 2, the fracture width of Lingshui gas field ranges from 0 to 464 μm, the particle size optimization design of wellbore strengthening material can be guided according to the predictive fracture width.

3. **Optimization of drilling fluid formula**

3.1. **Experiment device and method**

The fixed fracture width is usually used in traditional lost circulation simulation device. The circulation state of drilling fluid and fracture wall feature can be simulated by adding mixing rod or using natural core. While it ignores the influence of fracture expansion on the stability of the sealing zone. Based on the theory of fracture closure stress, a new simulation device was developed to simulate the dynamic propagation of fracture.

![Figure 3. Diagram of wellbore strengthening equipment.](image)

As shown in figure 3, the developed wellbore strengthening experimental device is mainly composed of crack module and injection pump, which can monitor the parameters of drilling fluid injection pressure, fracture closure stress, fracture outlet pressure and fracture width in real time. The
distribution and microstructure of the plugging zone can be observed after the experiment so as to investigate the effective plugging area.

3.2. **Optimization of particle size distribution**

Different particle size selection criteria are used to match with the predicted fracture width. The commonly used matching criteria include D50 criterion, D90 criterion, 1/3 criterion, Vickers criterion and Alsaba criterion [5-9]. The calcium carbonate is set as LCM. The specific definitions of different selection criteria are as follows.

D50 criterion proposed that the D50 value should be equal to maximum fracture width [5]. D90 criterion argued that the maximum fracture width is D90 value [6]. 1/3 criterion proposed that the D50 value should be larger than 1/3 of maximum fracture width [7]. Vickers criterion insisted that the D75 value should be smaller than 2/3 of maximum fracture width, D50 value should be larger than 1/3 of maximum fracture width, D25 value should be 1/7 of average fracture width and D10 value should be larger than minimum fracture width [8]. Alsaba criterion proposed that D50 value should be larger than 3/10 of maximum fracture width and D90 value should larger than 6/5 of maximum fracture width [9].

The basic slurry of the test experiment is composed of 4% bentonite slurry and 0.4% xanthan. The size of the LCM is 40-60 mesh and the initial fracture width of the wellbore strengthening test is 450 μm.

| Selection method | 32-40 mesh/% | 40-50 mesh/% | 50-65 mesh/% | 65-100 mesh/% | Invasion depth/cm | Pressure bearing capacity/MPa |
|------------------|--------------|--------------|--------------|---------------|-------------------|--------------------------------|
| D50 rule         | 0.71         | 0.71         | 0.71         | 2.86          | 0.53              | 7.30                           |
| D90 rule         | 1.45         | 1.32         | 1.58         | 0.65          | 0.79              | 4.09                           |
| 1/3 rule         | 2.5          | 0.83         | 0.84         | 0.83          | 1.56              | 3.13                           |
| Vickers rule     | 1.33         | 1.34         | 1.33         | 1             | 1.28              | 2.55                           |
| Alsaba rule      | 1.25         | 1.25         | 1.25         | 1.25          | 1.04              | 2.86                           |

As shown in Table 2, the optimal particle size matching criterion is D50 criterion. Based on the optimal particle size matching criterion, the addition of wellbore strengthening material is optimized, which is shown as Table 3.

| Content/% | Invasion depth/cm | Pressure bearing capacity/MPa |
|-----------|-------------------|--------------------------------|
| 3         | 0.53              | 7.30                           |
| 4         | 0.46              | 11.82                          |
| 5         | 0.43              | 15.87                          |
| 6         | 0.38              | 16.13                          |
| 7         | 0.36              | 16.91                          |

The test results show that the invasion depth decreases with the increase of LCM content and the pressure bearing capacity of fractures increases gradually. When the particle size reaches 5%, the invasion depth decreases and the pressure bearing capacity of fractures increase slowly. When the concentration of LCM is too high, the circulating frictional pressure may increase, which is not conducive to wellbore stability. Therefore, the optimal addition of LCM is 5%.
The compatibility of water-based drilling fluids was tested. The effect of LCM on the drilling fluid viscosity and fluid loss was analyzed.

Table 4. Performance of water-based drilling fluid with the effect of LCM (hot rolling at 150℃/16h).

| Formula                          | Condition          | AV /mPa·s | PV /mPa·s | YP /Pa   | Gel Pa/Pa | FL API /mL |
|----------------------------------|--------------------|-----------|-----------|----------|-----------|------------|
| Water-based drilling fluid       | Before hot rolling | 39.5      | 25        | 14.5     | 3.5/4.5   | 16.4       |
| Water-based drilling fluid       | After hot rolling  | 40.5      | 26        | 14.5     | 6/12.5    | 2.4        |
| Water-based drilling fluid + LCM | Before hot rolling | 45        | 30        | 15       | 4/7       | 10.4       |
| Water-based drilling fluid + LCM | After hot rolling  | 46        | 30        | 16       | 7/13      | 1.8        |

As shown in Table 4, after adding the optimized wellbore strengthening material, the viscosity of drilling fluid increase and the filtration rate of drilling fluid decreases, which indicates that the wellbore strengthening material improves the plugging effect of drilling fluid. It is conducive to improving the bearing capacity of the formation.

To further investigate the influence of LCM on the sealing performance of drilling fluid. The sealing results of seepage loss and fractured loss are shown in figure 4 and figure 5. The particle size of seepage loss experiment is 40-60 mesh and the drilling fluid will be tested with the condition of 0.7 MPa for 30 minutes.

As shown in figure 4, the optimized LCM has good plugging effect in seepage loss. The invasion depth is smaller than 0.3 cm.

The initial fracture width of developed fractured loss testing device is 450 μm. The fracture closure pressure is set as 1 MPa.
As shown in figure 5, the optimized LCM material has good sealing effect for fractured leakage and the pressure bearing capacity is more than 17 MPa with the fracture width of 450 μm.

4. Conclusions
Based on the wellbore strengthening theory and the stress seepage coupling theory of porous elastic media, a prediction model of fracture width was developed. Considering the influence of in-situ stress anisotropy, leakage rate and fracture pressure, the fracture width of Lingshui block ranged from 0 to 464 μm.

The drilling fluid formula with pressure bearing capacity of more than 17 MPa was developed through the optimization of particle size distribution and concentration. The optimized wellbore strengthening formula had good compatibility in water-based drilling fluid, which could form a tight sealing zone with strengthening network structure of force chain and significantly improve the pressure bearing capacity of fractured formation.

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