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Numerical investigation of a low-efficient hydraulic fracturing operation in a tight gas reservoir in the North German Basin

Lei Zhou [a,*], Michael Z. Hou [a,b,c], Yang Gou [a], Mengting Li [a]

[a] Energy Research Center of lower Saxony, Clausthal University of Technology, Goslar, Germany
[b] Sino-German Energy Research Center, Sichuan University, Chengdu, China
[c] Institute of Petroleum Engineering, Clausthal University of Technology, Clausthal-Zellerfeld, Germany

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ABSTRACT

In this paper, a hydraulic fracturing operation in the tight gas reservoir LZN in the North Germany Basin was numerically investigated to find out the reason for the weak productivity after the fracturing operation. For the investigation, a self-developed numerical model was used, in which rock formation, pore and fracture systems are coupled together. The hydro-mechanical coupling effect, the proppant transport and settling as well as their influences on the fracture closure and contact were fully considered. In the numerical modeling of the in situ operation, the whole process of the data and the main fracturing including fracture propagation, closure, contact and proppant transport were simulated. The modeling was based on the history matching of the derived bottom hole pressure (BHP) from the measured treating pressure. According to the final placement of the proppant and the width distribution after 1500 min, it was found that the middle part of the fracture around the perforation was fully closed after shut in. It indicates that the operation is unsuccessful for the production enhancement; because the connection between the borehole and the created fracture is weak. If the perforation would have been set 15 m lower, then a successful operation with a better connectivity between the borehole and the propped fracture would have been achieved. The precondition to move down the perforation is that the lower fracture barrier must be thick and has a much higher minimum horizontal stress to prevent the fracture going through it. This requirement is also fulfilled in the case study.

1. Introduction

In Germany the domestic gas production still covers 12% of the annual demand. A part of the production comes from tight gas reservoirs. The most tight gas reservoirs in Germany are located in the North German Basin under 3500 m and consist of layered sediments, such as Bunt- and Rotliegend-Sandstone. The permeability of the reservoirs is generally below 1 mD. It is too small for an economical production. Therefore artificial flow paths are essential. In a field operation, pressurized fluid will be injected into the rock formation to create the flow paths, which is called hydraulic fracturing. In the North German Basin, the rock formations of the tight gas reservoirs are intact with few nature fractures. In addition, the vertical stress exerted on the rock formations amounts to the largest principle stress. Therefore a tensile fracture perpendicular to the minimum horizontal stress will be generated as a result of the fluid injection. In the meantime, solid proppant will be added in the fluid to prevent the complete closure of the fracture after pumping has been stopped and fracturing fluid has leaked into the formation.

The object of the study is a tight gas reservoir called LZN in the North German Basin near the North Sea. It is located at the depth of 4360 m and is layered with varied sandstone, silt and shale. The reservoir permeability is in a range from 0.01 mD to 1 mD. In order to enhance the gas productivity, a hydraulic fracturing operation was performed in 2009. During the operation, 425 m³ fluid and 86 t proppant were injected into the formation. However, the productivity after the operation did not significantly increase. The reason is still unknown today; because there is no opportunity and practical measuring method to get a full view of the created fracture pattern and the final proppant placement in the reservoir. Thus mathematical analysis and assessment play an important role.

Generally hydraulic fracturing involves the following physical processes: mechanical deformation, induced by pressure change in fractures and pores; fluid flow within fracture and formation, including their interactions; fracture propagation; as well as proppant transport and settling inside the fracture. From 1950s onwards, mathematical models to simulate hydraulic fracturing propagation were developed one after another, e.g. KGD and PKN 2D models, lumped and cell based pseudo-3D models, planar 3D

* Corresponding author. Tel.: +49 5321 38168114; fax: +49 5321 38168196.
E-mail addresses: lei.zhou@efzn.de, zhoulei84@hotmail.com (L. Zhou).

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model as well as full 3D model. They were solved by analytical, semi-analytical or fully numerical methods respectively. There is a comprehensive review in Adachia et al. (2007), Economides and Nolte (2000), Perkins and Kern (1961), Nordren (1972), Fung et al. (1987), Cleary (1980), Cleary et al. (1988), Peirce and Siebrits (2001), Siebrits and Peirce (2002), Zhou and Hou (2013). On the other side, some proppant transport models were developed from 1990s, e.g. Barree and Conway (1995) developed a convective transport model based on the density variation. Gadde and Liu (Gadde et al., 2004; Gadde and Sharma, 2005; Liu, 2006) used the corrected Stokes settling model and the relative proppant/fluid velocity model derived from experiments to describe the proppant movement. Hsu et al. (2012) provided a more physic-based transport model by solving the simplified Navier–Stokes equations for two phases.

In a tensile fracture, the fracture aperture without proppant support can be reduced to almost null at the full closure stage. Therefore the final proppant placement plays the most important role for production enhancement. The most commonly used simulators in the PE industry are FracPro and MFrac. According to our experiences, both of them cannot reasonably simulate the full fracture closure, especially contact with proppant. In FracPro, the proppant will fill the created fracture after full closure; but in reality, the proppant will descend to the lower part of fracture due to the settling effect. It indicates that the area of the proppant placement is overestimated. The developed model in Adachia et al. (2007) has the same problem as FracPro. In MFrac, the simulation will be forced to stop, when the proppant reaches its maximum compaction, even a big area of the fracture in the upper part is still open without proppant. It indicates that the area of the proppant placement is underestimated. The problem in these models is that they are not considering the hydro-mechanical conditions under contact. In fact, the fluid pressure in the fracture under contact could be smaller than the normal stress perpendicular to the fracture wall. Therefore it is difficult to force the compact proppant to the upper part of fracture during the closure process. In this paper we used a self-developed 3D hydraulic fracturing model to investigate the operation in the tight gas reservoir LZN. This model is a secondary development of the one in Zhou and Hou (2013), which considers fracture propagation in the 3D geometric model under 3D stress state and fully hydro-mechanical coupling effect between fracture and matrix. In the new model, proppant transport with settling effect and fracture contact in consideration of proppant placement were further implemented. By using this model, the fracturing operation from injection beginning till full closure in the tight gas reservoir LZN was numerically simulated. Then the fracture conductivity and the connection between the perforation and the created fracture were evaluated based on the modeled final proppant placement.

2. Governing equations

2.1. Governing equations for mechanical deformation

The 3D mechanical calculation is based on the elasto-plasticity theory. The key point is solving the equation of motion (Eq. (1)) in a dynamical process to get the displacement increment in a time interval. By using continuum (Eq. (2)) and constitutive equation (Eq. (3)) the strain and the stress increment could be further estimated. The numerical formulation is described in Appendix I.

$$\sigma_{ij,j}+\rho(b_i-(dv_i/dt))=0 \tag{1}$$

$$\Delta\varepsilon_{ij}=(1/2)(\Delta u_{i,j}+\Delta u_{j,i}) \tag{2}$$

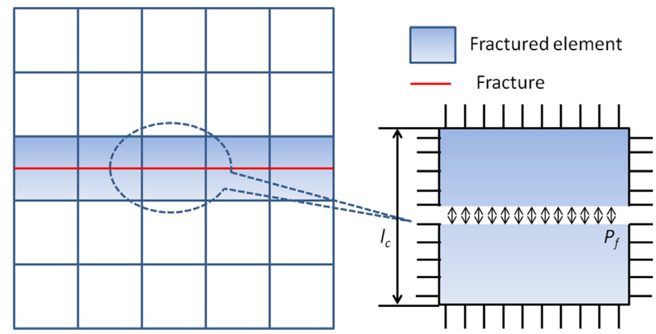

Fig. 1. Demonstration of fracture elements in the geometrical model (left) as well as the load condition in one fracture element at the frozen time point (right).

$$\Delta\sigma'=D\Delta\varepsilon \tag{3}$$

where $\sigma=\sigma'+\alpha IP_p$, σ is total stress [Pa]; ρ is density [kg/m³]; b_i is gravity acceleration [m/s²]; v_i is velocity [m/s]; $\Delta\varepsilon$ is strain increment [dimensionless]; u is displacement [m]; $\Delta\sigma'$ is effective stress increment [Pa]; α is biot-coefficient [dimensionless]; I is unit matrix; and D is physical matrix;$i,j\in(x,y,z)$.

As introduced in Zhou and Hou (2013), an extra strain increment induced by pressure change in the fracture was added in the total strain increment to describe the discontinuous behavior of fracture. Let us consider a tensile fracture penetrating through the center of one row elements in Fig. 1. Due to fluid flow or leak off, the fluid pressure in the fracture changes. The momentary mechanical response of the rock formation happened firstly only on the fracture walls and then transferred to the far field by elastic wave. In the model, it is assumed that the elements within fracture deform immediately after the fluid pressure changes. The remaining elements are not affected. It indicates that at this frozen time point, the fracture elements are constrained as shown in Fig. 1. The pressure change will only lead a strain change in the direction perpendicular to the fracture. Under such conditions, the strain change perpendicular to the fracture can be expressed as follows:

$$\Delta\varepsilon_f=\frac{P_f(t+1)+\sigma_n(t)}{\alpha_1} \tag{4}$$

where ε_f is strain induced by change of fluid pressure in fracture [dimensionless]; P_f is fluid pressure in fracture [Pa]; and σ_n is normal stress perpendicular to the fracture [Pa].

According to Hook's law, the change of the stress in the three orthogonal directions at this time step is then

$$\sigma_n(\text{new})=\sigma_n(\text{old})-\alpha_1\Delta\varepsilon_f \tag{5a}$$

$$\sigma_{1,2}(\text{new})=\sigma_{1,2}(\text{old})-\alpha_2\Delta\varepsilon_f \tag{5b}$$

where $\sigma_{1,2}$ is stress in another two principal directions.

If the element dimension normal to the fracture is small, then the change of the fracture width can be approximated as follows:

$$\Delta w=\varepsilon_f l_c=\frac{P_f(t+1)+\sigma_n(t)}{\alpha_1}l_c \tag{6}$$

where w is fracture width [m] and l_c is element length normal to the fracture [m].

As Eq. (6) states, if the fluid pressure is larger than the absolute value of the normal stress, then the fracture width will be enlarged and if smaller, it will be reduced. However the width reduction has limitation. In fact if the proppant concentration reaches its maximum value (compacted proppant) or the present fracture width is below the residual (it infers that the fracture wall has already made contact with proppant or its self); then no width reduction will happen, even if the normal stress is larger than the fluid pressure. In the meantime, a contact stress was built, which must