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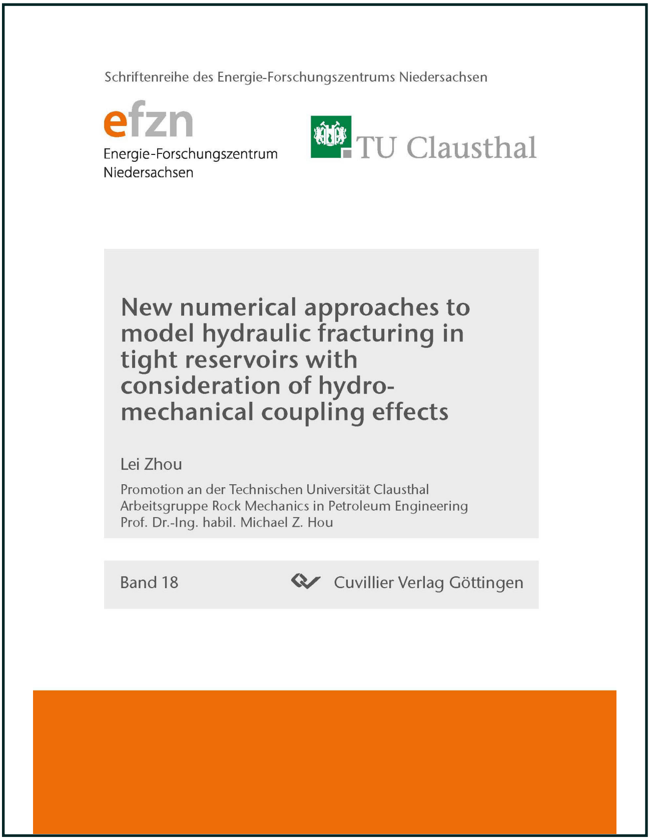
New numerical approaches to model hydraulic fracturing in tight reservoirs with consideration of hydro-mechanical coupling effects



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1 Introduction

Hydraulic fracturing is a very important problem, especially in petroleum industry, e.g. in tight gas reservoir, whose permeability is too small for an economical production. Therefore a man-made conductive channel or so called fracture is essential. In field operations, a completed well will be firstly perforated; then pressurized fluid will be injected into rock formation to create the fracture. In the meantime, solid proppant will be added in the injection fluid, in order to prevent completely closure of the fracture wall after pumping has been stopped and the fracturing fluid has leaked off.

Generally fracture orientation depends only on in situ-stress state. A hydraulic fracture growths always in the direction perpendicular to the maximal principal stress (in this dissertation, compressive stress is assigned as negative), where the propagation resistance is lower than in other direction. In a layered tight gas reservoir, the primary in-situ principal stresses are normally assumed to be oriented in the vertical and the horizontal directions. They are so-called vertical, minimal und maximal horizontal stresses. Normally the maximal and the minimal horizontal stresses are smaller than the vertical (The maximal horizontal stress is the intermediate one). Under such stress state, a two-wing planar artificial fracture oriented in the direction perpendicular to the minimal in-situ horizontal stress will be created (Fig. 1.1).

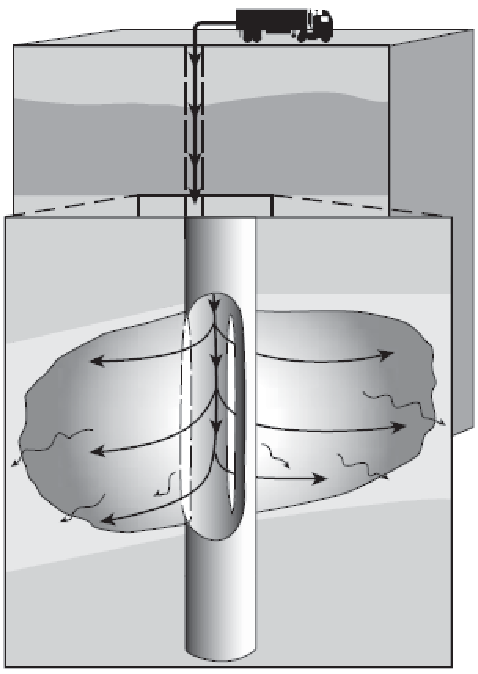

Figure 1.1 Demonstration of the hydraulic fracturing in petroleum Engineering [1]

Thanks to the rapid development of the new technologies, at present it is possible to drill a horizontal well over 1000 m. It is normally used to improve well production. However fracturing a horizontal well is still necessary in a tight gas reservoir. In a horizontal well,

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multiple-stage fracturing concept is preferred. In this concept, 8 to 12 hydraulic fractures along the horizontal well will be planed. They have an interval of ca. 100 ml to avoid the influence between each other. Because fracture orientation is only dependent on its related in-situ stress state, therefore control of the final multiple fracture pattern should be considered in design with respect to well trajectory. On one side, if a horizontal well is drilled into the direction of the maximal horizontal stress, then a longitudinal multiple fracture system will be created (Fig. 1.2), on the other hand if a horizontal well is oriented into the direction of the minimal horizontal stress, then a transverse multiple fracture system (Fig. 1.3) can be obtained.

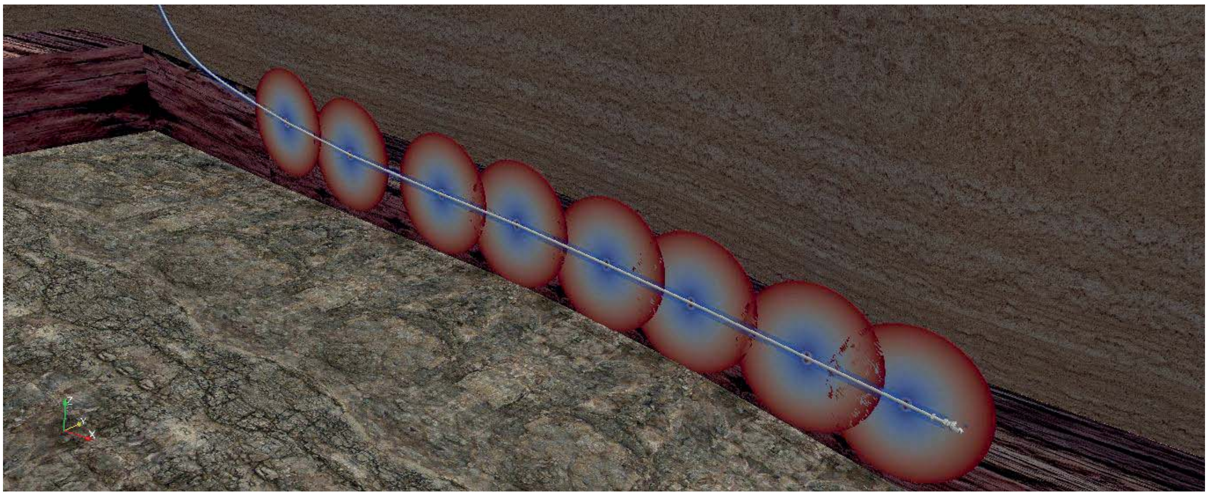

Figure 1.2 Demonstration of a longitudinal multiple fracture system

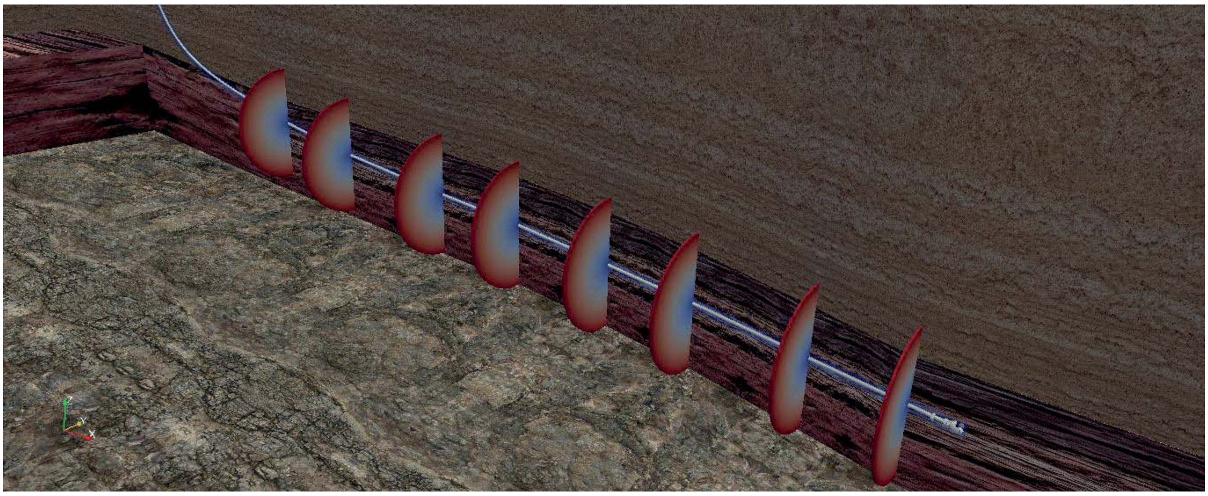

Figure 1.3 Demonstration of a transverse multiple fracture system

The key design parameter of a hydraulic fracturing operation is the fracture propagation area especially propped area in the reservoir. Normally we need such man-made fracture, which propagates much longer in the horizontal direction rather than in the vertical. Thus the reservoir could be maximally stimulated and the cap rock could stay intact. Therefore it’s necessary to design hydraulic fracturing operations on the basis of in-situ condition. Due to geological complexity and large scale dimension it involves, it’s not possible to investigate

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and design a fracturing operation through experimental methods neither in labor nor in situ. Thus mathematical analysis and numerical modeling play the most 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 a fracture. The governing equations for each process will be introduced in chapter 2.

In chapter 3 there is a comprehensive review of the mathematical models for hydraulic fracturing. From 1950s, mathematical and numerical models to describe fracture propagation were developed one after another, e.g. the KGD and the PKN 2D models, the lumped and the cell based pseudo 3D models as well as the planar 3D model. There are solved by analytical, semi-analytical or fully numerical methods respectively. Proppant placement is another important factor to design hydraulic fracturing. The investigation of the proppant transport process has been done through many laboratory experiments. Some numerical models were developed based on the experimental results closure pressure

Most models used today for simulating hydraulic fracture propagation might certainly not represent the reality, as they strongly rely on the assumption of plain strain state; including a regular stratigraphy of layered horizontal rock formations with homogenous rock materials; uniform closure pressure in each individual layers; negligible influence of fluid leak-off in stressed rock mass; no consideration of the influence of the porous flow on the fluid leak-off, the influence of proppant on the fluid rheology, as well as the influence of proppant on the fracture closure. Besides they consider only a single hydraulic fracturing, which has difficulties to analysis a multiple fracture system, because the influence of neighbor fractures cannot be considered.

To overcome the above mentioned weak points, a more physical based numerical approach to model in-situ hydraulic fracturing operations from injection begin till fracture closure was developed in my dissertation work and will be presented in chapter 4. This approach is more like the planar 3D model with fixed mesh and assumed fracture propagation, yet in 3D geometry and stress state with inhomogeneous material behavior and is solved with fully hydro-mechanical coupling by using a hybrid combination of the finite difference method (FDM) and the finite volume method (FVM) in a quasi-static formulation. It is also possible to generate multiple hydraulic fractures in one geological model with none-uniform in-situ conditions, such that fracture propagation in a multiple fracture system could be numerically analyzed.

In fact, orientation of a hydraulic fracturing is not always straight forward. It could be affected by many factors, such as perforation, change of primary stress state etc., e.g. if perforation direction deviates to the minimal in-situ horizontal stress, the fracture propagates firstly along the perforation and then gradually turns to the direction of minimal in-situ horizontal stress (Fig. 1.4). Another example is fracture reorientation in re-fracturing process. During a long term field production, the conductivity of the created fracture will decrease because of the embedment of proppant into rock formation and the increasing of wall stress forcing fracture

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closure. Therefore a re-fracture operation is necessary after production in several years. Before re-fracturing, pore pressure decreases irregularly in the whole reservoir due to production, which leads to irregularly decrease of principal stress and finally a reverse stress orientation [3, 4]. Thus the growth of the re-fracture will be affected and then reoriented due to the redistributed stress state (Fig. 1.5). Further more in a multiple hydraulic fracturing treatment, if the distance between each injection position is not long enough, the fracture orientation could be also influenced by its neighbor [5, 6] (Fig. 1.6).

Reoriented fracture has certain influence on productivity. The determination of the accurate growth route of a re-fracture is the basis and the precondition for production investigation and optimization. However there is still no effectual simulation tool to accurately and physic-logically model reorientation process under fully hydro-mechanical coupling. In my dissertation work, a 2D simulator based on the extended finite element method (XFEM) and the finite volume method was developed to the model hydraulic fracture propagation with arbitrary orientation. It will be presented in detail in chapter 5.

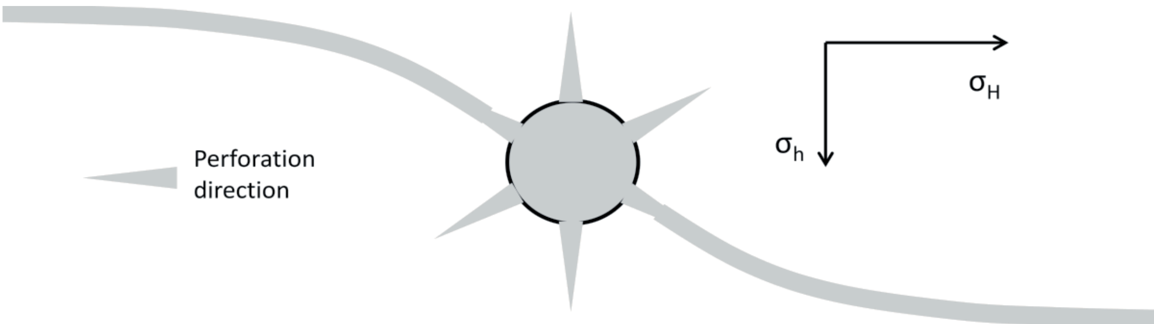

Figure 1.4 Demonstration of fracture reorientation due to perforation

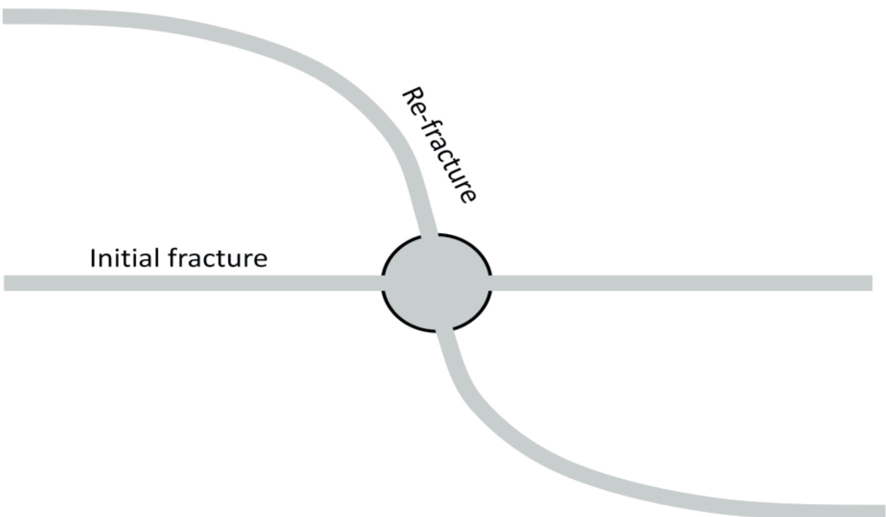

Figure 1.5 Demonstration of fracture reorientation due to stress change induced by production

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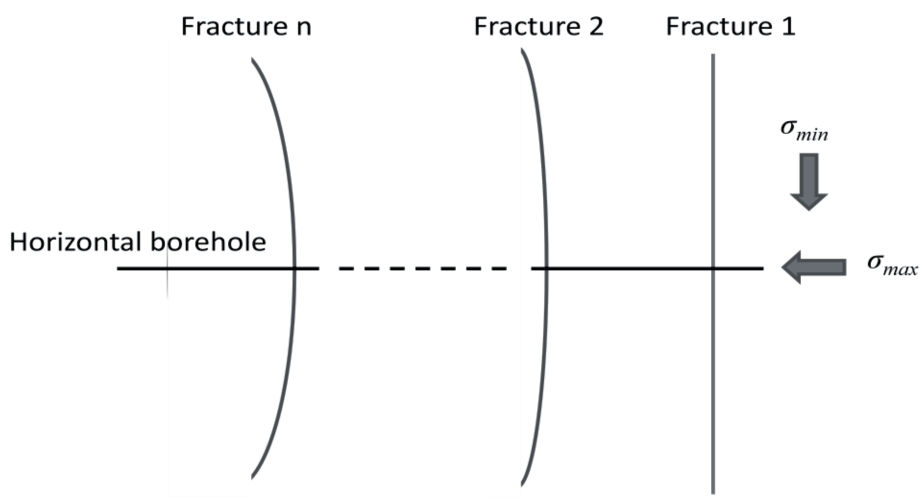

Figure 1.6 Demonstration of fracture reorientation due to influence of neighbor fractures

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