1
Introduction

1.1.
Hydraulic fracturing in naturally fractured formations

Hydraulic fracturing (or hydraulic stimulation) is an operation that consists in the injection of a fluid under high pressures into the reservoir rock to generate tensile stresses in the rock, initiating a fracture. This fracture keeps growing during fluid pumping. Combined with the fracturing fluid, a granular agent (proppant) is injected. When the fracture closes its faces against this agent once the pumping operation stops, a high conductivity channel forms in the fracture for the flux of hydrocarbons from the rock to the well. This is one of the most important activities in hydrocarbons extraction nowadays.

According to Valkó and Economides (1995), 50% oil wells and 70% gas wells were stimulated using this technology during the second half of the 20th century. Considering the huge increase in unconventional reservoirs during the past 15 years, one may assume those numbers have further increased. Nowadays, this technique may be applied for different purposes, such as: (a) the stimulation of rock formations with poor or damaged permeability, mainly in shale gas reservoirs, to increase conductivity between the reservoir and the producing wells, (b) improvement of produced water re-injection where water is injected to replace produced fluids and maintain reservoir pressure or provide enhanced oil recovery, (c) cuttings reinjection where a slurry of drill cuttings is injected into a formation to mitigate the cost and risk of surface disposal, (d) in-situ stress measurement by balancing the fracturing fluid pressure in a hydraulically opened fracture with the geostatic stresses, and (e) wellbore integrity analysis of drilling operations to avoid propagating near-wellbore fractures that could result in drilling fluid losses to the formation and to inability to effectively clean the wellbore (Zielonka *et al.*, 2014).

Hydraulic fracturing may be applied on a wide depth range, being more common in depths between 2000 and 3500 m. Horizontal, vertical or even inclined wells are used to create longitudinal or transversal fractures, and one or multi-stage treatments can be applied, depending on a variety of factors. As Figure 1.1 shows, fractures grow preferably in the direction perpendicular to the minimum in situ stress.

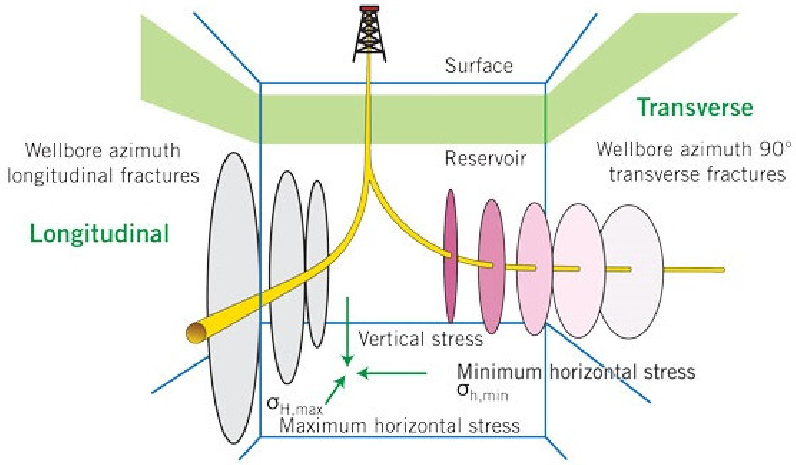

Figure 1.1 – Fracture development as function of wellbore orientation (Rahim et al., 2012).

Most sedimentary rocks are composed of layers which reflect the changing depositional conditions of geological time. In addition, the more competent rocks frequently are fractured and jointed as the result of structural deformations or tectonic movements. Evidence of such joint systems exists in many surface outcrops, and it can be assumed that similar systems occur in many subsurface rocks, although the individual joints may be rather tightly closed due to overburden forces (Lamont and Jessen, 1963).

An effective hydraulic fracture treatment in naturally fractured reservoirs should cross and connect the natural fracture system, increasing the effective surface area of the wellbore and consequently its production. However, those interactions may also interfere and inhibit fracture growth and proppant placement, having an adverse effect on the production rates, increasing the treatment costs. Consequently, the behaviour of hydraulic fractures (HF) near a natural fault or discontinuity (NF) is of great importance for an efficient reservoir simulation, as natural discontinuities can significantly influence the hydraulic fracturing process (Zhang and Ghassemi, 2011). Along the last decades, laboratory experiments have described qualitatively the effects of fracture intersection (Blanton, 1982; Gu *et al.*, 2012; Khoei *et al.*, 2015), showing three types of interaction features: crossing to the opposite side of the NF, arresting of the hydraulic fractures (HF) and opening of the natural fractures (NF). Figure 1.2 illustrates the events that can occur. As the interaction between fractures depends on several physical parameters, such as in-situ stress and angle between fractures, a realistic simulation of the treatment is needed to improve design and consequently production.

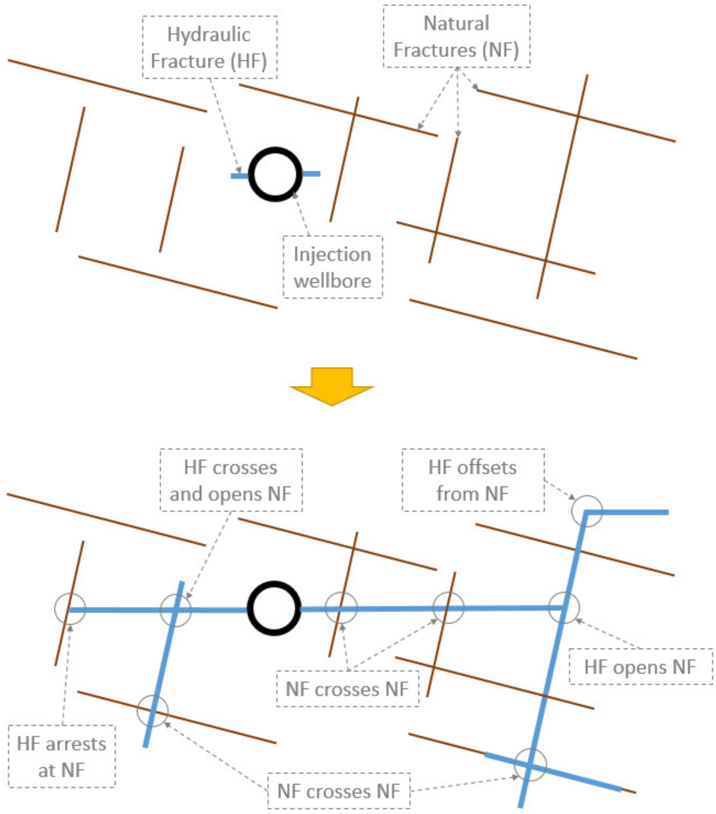

Figure 1.2 – Different events of interaction between hydraulic and natural fractures

1.2. Research motivation

Modern methods of simulation and prediction of hydraulic stimulation of geomaterials are still very limited to academic cases. Most commercial software used by the industry are focused in rapid design and still resort to very simple formulations (Warpinski *et al.*, 1993) that assume planar fractures with simple geometry with one-dimensional decoupled leak-off in linear-elastic impermeable materials.

As stated by Adachi *et al.* (2007) there is a rising tide of evidence from direct monitoring of actual field treatments that suggests that the fracture can grow in a complicated manner, taking advantage of local heterogeneities, layering, and natural fracture networks in the reservoir. These factors complicate and make the process of treatment design and numerical modelling far more challenging.

Numerical methods have been widely used to simulate hydraulic fracturing treatments. Although many different academic works use techniques such as the Boundary Element Method or the Discrete Element Method, the Finite Element Method takes by far the preference of most researchers. The techniques for modelling fracture propagation within the finite element framework are mainly based on: adaptive meshing, interface or cohesive elements, damage models and enrichment techniques.

One very well-known enrichment technique is the eXtended Finite Element Method (XFEM), which was introduced by Belytschko and Black (1999) and Moes and Dolbow (1999) and later applied to model propagation of hydraulic fractures in quasi-brittle materials by Moës and Belytschko (2002). Even though very interesting results were achieved, there are still many "grey" areas of knowledge, such as the branching and intersection of fractures, fluid flow related to fractures, and the effects of rock heterogeneities (Li *et al.*, 2015).

Considering all the mentioned limitations in the available methods for hydraulic fracture simulation and the many parameters that govern HF behaviour, the motivation for this research is the possibility of using a recent and advanced numerical technique such as the XFEM to bring better insight in the subject of numerical modelling of hydraulic stimulation in naturally fractured reservoirs.

1.3. Research objectives

This research work aims at the development of a finite element to study the interaction between hydraulic and natural fractures. The proposed finite element uses enrichment techniques to represent displacement discontinuities, i.e. fractures. By increasing the number of enriched variables, multiple intersecting fractures may be represented in one single element. Thus, the element is capable of simulating not only multiple fractures in the same model but also fracture intersections, as the ones showed in Figure 1.3.

Other complex phenomena are considered, such as fracture frictional behaviour, fully coupled behaviour with pore and fracture fluid pressure, exchange of fluid between the fracture and the surrounding medium and the consideration of an eventual loss of pressure between the fracture faces and the porous medium (filter cake). The simulation of the mentioned phenomena is achieved by discretizing the finite element problem with three physical variables: displacements, pore-pressures and fracture pressures.

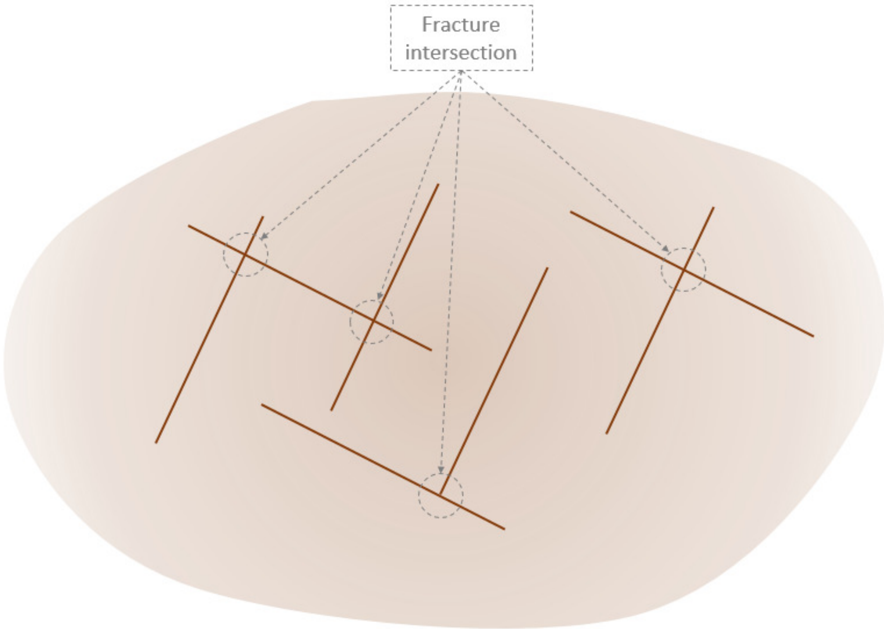

Figure 1.3 – Fracture intersections in a fractured medium

The implementation of an enriched element requires additional procedures that deal with fracture geometry. This is achieved by implementing a pre-processor and a post-processor. The former defines the global location of the fractures, their intersections with each other and intersections between fractures and the element mesh. The latter checks for fracture propagation by computing a propagation criterion based on the stress state.

The element implementation and the mentioned procedures are integrated with the software Abaqus (Simulia, 2014) as user subroutines, together with input and output auxiliary codes, resulting in a numerical simulation suite which is named XFEMHF. This overcomes the limitations of built-in Abaqus XFEM elements, which cannot be intersected by more than one fracture. Similar but simpler implementations of this type were also done by other authors with good results (Giner *et al.*, 2009; Chen, 2013; Silva, 2015).

In addition to the implementation work, a wide variety of numerical applications are computed for validation and to prove the applicability of the numerical tool. In most of the presented models, parametric analyses are run.

Summing up, the objectives of this thesis may be summarized in:

- Formulation and implementation of an XFEM element that is capable of simulating
    - multiple fractures, including intersections;
    - fracture frictional behaviour;
    - fully coupled behaviour with pore and fracture fluid pressure;
    - exchange of fluid between the fracture and the surrounding medium;
    - an eventual loss of pressure between the fracture faces and the porous medium (filter cake);
- Implementation of a pre-processor for definition of fracture geometry;
- Implementation of a post-processor for propagation computing;
- Integration of the implemented code with Abaqus software;
- Validation of the formulation comparing the implemented code with analytical or other software solutions;
- Application to real cases or synthetic models.

Finally, this research work aims at contributing to improve knowledge on the subject of intersection between hydraulic and natural fractures, mainly in unconventional reservoirs. The use of a more advanced numerical tool may bring better prediction of injection pressure, injected volumes, fracture opening and fracture network pattern, resulting in improved treatment design. The application to parametric studies of real cases may also clarify in which scenarios of stimulation the treatment is more effective and the production optimized.

1.4. Thesis organization

This thesis is organized in seven chapters. The first chapter introduces the research, its motivations and objectives. The second chapter presents the basic concepts and the most relevant research works that give support to this research, namely hydraulic fracture modelling, intersection between hydraulic and natural fractures and the eXtended Finite Element Method.

The third chapter presents the theoretical background and develops the formulation of the proposed element, focusing on the special spatial discretization that the XFEM requires of the governing equations. The constitutive model used to simulate the behaviour of the natural fractures is also presented. Chapter 4 describes the most important aspects and details of the implementation of the XFEMHF algorithm and its components. It also describes the interaction of the implemented code with the software Abaqus and the limitations associated to it.

The fifth chapter presents the comparison between numerical models and analytical solutions or other software, in order to validate the implemented formulation. Finally, tests in three models are used to verify the accuracy of the contact and friction model for natural fractures.

Chapter six presents applications to more realistic cases. It starts by comparing numerical models with two sets of experimental tests by Blanton (1982), and Khoei *et al.* (2015). Then, a synthetic multi-fractured model is subjected to a parametric analysis of the in-situ stresses and initial fracture hydraulic aperture. Finally, a model of percolation under a dam foundation is set and different parameters are tested to study their influence, including a comparison with the results of Segura and Carol (2004).

In the last section, the main conclusions are summarized. Proposals to further develop and improve the implemented algorithm of this research are also presented and discussed.