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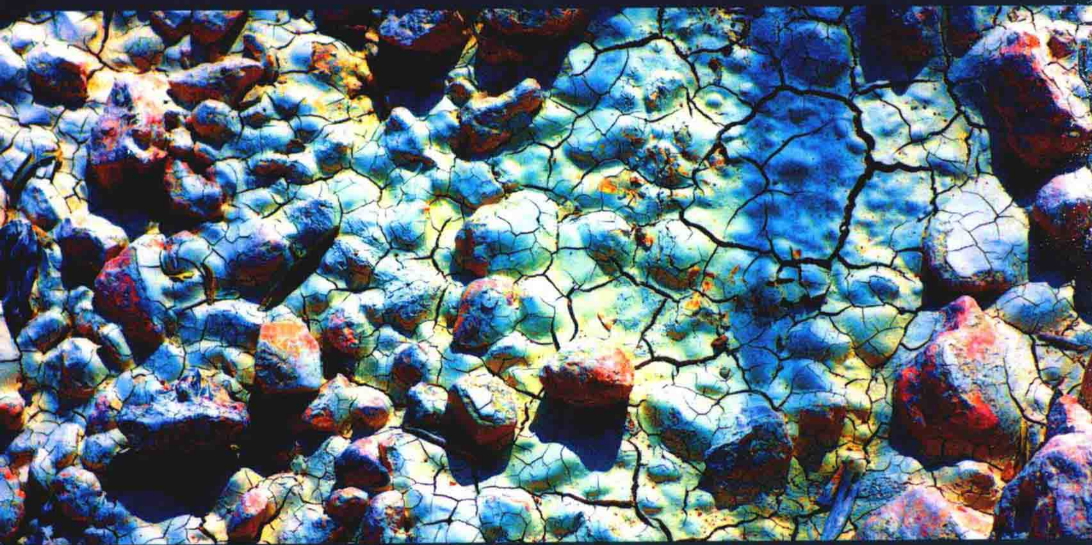

Electrohydraulic Fracturing of Rocks

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Preface

Early in 2005, Total Exploration Production issued a call in France for "Blue Sky" research proposals dedicated to stimulation techniques for tight gas reservoirs. In such very tight formations, the permeability being in the sub milli-Darcy range, hydraulic fracturing was found to be inefficient. After fracturing, a rapid decay of gas production was observed. The general understanding was – and still is – that in a tight formation, hydraulic fracturing produces drains with high permeability but they are connected to a tight formation. Once gas has been expulsed from the neighborhood of the fracture, the flow decreases dramatically and it is still the tighter part of the formation that controls the production.

Some solutions for circumventing this problem were known, one being to drill closely-spaced wells so that after hydraulic fracture, the neighborhood of the cracks from which gas can be extracted overlap, ensuring that as many hydrocarbons as possible are produced. Obviously, this solution is expensive, since the number of wells to be drilled increases and it is also a bit risky. During hydraulic fracture, we should avoid directly connecting one well to another by a fracture.

Through its call for proposals, Total Exploration Production was looking for alternatives, hoping that they would be more cost-effective than classical hydraulic fracturing.

At that time, only one of the authors of this book was involved in petroleum engineering. Our backgrounds were in electrical, civil and mechanical engineering. It is most probably because of this diversity that we collectively answered this call with a project on electrohydraulic fracturing. It was a mix of our respective backgrounds on pulsed arc electrical discharges (e.g. for material recycling purposes), dynamic analysis of structures, failure of civil engineering structures and assessment of tightness of nuclear vessels. We felt that one possible answer to the problem would be to generate a dense distribution of connected microcracks in rocks instead of a few large fractures. In other words, we thought that fragmentation of rock was more appropriate than fracture of rocks in such a problem. Dense and connected microcracking was expected to increase the permeability in the volume of the rock, and therefore would be more effective for gas production than a few drains (fractures) in a tight formation.

This proposal received support and enthusiasm from Total Exploration Production and a feasibility study started in 2007, followed after that by more comprehensive research spanning from 2008 to 2012. The research project was placed under the umbrella of the federation of research laboratories dedicated to petroleum engineering at the University of Pau, in connection with the Institute of Civil and Mechanical Engineering at Centrale Nantes. It also received the support from the Région Aquitaine, which helped with a doctoral fellowship and with additional support for the setting up of a comprehensive laboratory facility in Pau and Anglet.

The experimental program was probably the most demanding part of the project, but soon it revealed that our initial idea was correct. Over 300 specimens were tested under various conditions, each one following a specific workflow combining different testing techniques aimed at the characterization of dynamic loading, of the microstructure of the specimens and their permeability. Specimens were carried back and forth between the two sites in Pau and Anglet and also between the Total Exploration Production scientific and technical research center in Pau, where part of the study was performed, and our facilities at the university. Overall, the project involved over 10 people.

With positive results, the limits of the technique also emerged. With the first computations on representative reservoir geometries performed, we soon found that the damage zone around the well was too small because of the attenuation of the pressure waves generated by the electrical discharges. Therefore, we tried to investigate some optimization directions. There was also the frustration of not being able to carry out *in situ* experiments in order to check the feasibility of electrohydraulic fracturing in a real environment, or at least in a calibration chamber.

This book collects the various results obtained in the course of this project in a single monography. It is based on a compilation of several technical papers published from 2010 to 2015 [MAU 10, CHE 11, CHE 12, CHE 14b, CHE 14a, KHA 15]. The final chapter, however, is entirely original as the results have not been published.

At the time we started this project, unconventional resources, and more specifically shale gas, were not on the front pages of newspapers. Very soon, we thought about the implementation of the electrohydraulic technique to horizontal wells and shale gas production and two international patents were filled [REY 12, REY 12]. In 2011, the debate about the dangers of hydraulic fracturing developed in France, before and after it was banned, and unexpectedly electrohydraulic fracturing came to the forefront of discussions, being considered a potential alternative to hydraulic fracturing.

A lot has been written in the media about the promises of electrohydraulic fracturing, sometimes in a quite optimistic way. The critical approach, which ought to be that of scientists, pushes us to underline the limitations of this new technique, which would not be effective without a complementarity with hydraulic fracturing, as well as its potential provided that additional research and development can be carried out – not so easy a task in the French context. It is also the purpose of this book to collect results together so that readers can develop their own point of view about electrohydraulic fracturing.

Gilles PIJAUDIER-CABOT

December 2015

Introduction

I.1. Context

Hydraulic fracturing is used not only for the production of hydrocarbons, but also for geothermal energy production or fresh water production. It was implemented for the first time in 1947 in Kansas. Two years later, the first commercial fracturing treatments were conducted in oil wells in Oklahoma; but, it was only with the massive exploitation of shale gas, during the last decade, that the process became popular in the media outside the circle of experts. In 2008, over 50,000 well fractures were carried out around the world and it is estimated that over one in every two wells drilled today undergoes a fracturing treatment.

Hydraulic fracturing involves the high pressure injection of a fluid in a wellbore, at a specified depth. When the pressure applied by the fluid is greater than the lithostatic gradient (weight of the rock above the place where the pressure is applied) and the local resistance of the rock, a fracture is created that can extend over several hundred meters, provided that enough fluid is injected to maintain a sufficient pressure. During the process, a *proppant* (generally grains of sand or ceramic) is injected to prevent the crack from closing. Drilling water contains additives suited to the type of rock encountered, to facilitate the fracturing operation and to prevent the closure of the cracks created. These cracks act as drains, granting access to volumes of rock located a long way from the wellbore, but close enough to the created drain.

Hydraulic fracturing was first applied to conventional geological reservoirs. However, its use in low-permeability formations called tight gas reservoirs (TGRs), which are a thousand times less permeable than conventional reservoirs, has meant overcoming severe problems. Tight gas reservoirs and shale gas reservoirs contain gas mainly, stored in low-permeability rocks (0.1 mD). Hydraulic fracturing generates a few large cracks and gas may migrate toward these cracks and bubbles be produced. The extracted gas originates from a volume of rock near the surface of the fracture, through which the gas migrates due to the difference in pressure. Gas production consists of draining this zone where permeability is low. The gas trapped between the drained areas remains inaccessible. Once drainage is carried out, the production undergoes a very rapid decline.

The questions raised by hydraulic fracturing in the context of unconventional resources concern several issues. First, the rise of methane to the ground surface or to water tables has fueled public debate, although the extent of the phenomenon is still being discussed. The second issue concerns the water used during the fracturing process. It contains chemical elements that have been used for the fracturing process or dissolved from the underground host rock. This water ought to be stored safely on the surface and subsequently treated. Third, hydraulic fracturing may induce seismicity. The injection of water has reactivated existing faults in some cases in Switzerland and Great Britain. Finally, and probably more importantly, extracting gas with a sufficiently attractive economical benefit calls for a large number of wells that are closely spaced, and thus for a concentration of infrastructures within a dense logistic network is required to provide water and drilling equipment. Therefore, the environmental impact may be severe, particularly in protected or densely inhabited areas.

Under these circumstances and while waiting for the necessary feedback from experience, some European countries have banned hydraulic fracturing, opening the path to research on potential alternatives.

A first option is to change the fracturing fluid. The penetration of the fracturing fluid in the porous host rock depends directly on its viscosity. By reducing this parameter, the fluids more easily penetrate the porous rock and then if we apply enough pressure, induce a dense crack system. This principle being set, the problem resolves around finding the "right" fluid. There are many candidates such as propane, nitrogen, carbon dioxide, etc. In its liquid state, carbon dioxide has a viscosity 10 times lower than water; in the supercritical state (normal conditions of deposit), its viscosity is even lower. Each solution has benefits, beyond the simple fact that the fracturing fluid is no longer water and that, strictly speaking, we can no longer call it "hydraulic fracturing". Nitrogen is not harmful for the environment, and using carbon dioxide can help store it at the same time. There are also disadvantages: replacement fluids are more compressible than water, which makes the process less efficient; carbon dioxide can recombine with water and form a corrosive acid that may corrode the surrounding carbonate rocks.

The second approach is dynamic loading. In statics, the surface of a crack created in a material is proportional to the energy transferred to the volume of material that will break. Dynamic loading, however, forces, a large amount of energy into a small volume of material. In this volume, and because there is such a large amount of energy, a large area of cracks will be created, inducing a dense fracture network. As the loading wave spreads inside the material, it will therefore cause fragmentation, thereby connecting the initial and newly-created network of cracks. In quasi-brittle materials such as rocks, damage generated by dynamic loads results in distributed microcracking compared to damage generated by static loads, which is localized and consists of large cracks. On the basis of this observation, the objective is to use dynamic loads to generate distributed damage around a borehole, i.e. dense microcracking which should subsequently increase the rock permeability [CAO 01a, CAO 01b, DEN 02].

Dynamic loading can be induced, for example, by explosives placed in the wells. There is another possibility, on which we will focus in this book: dynamic loads generated by pulsed arc electrohydraulic discharges (PAEDs).

I.2. Principle of the technique and illustrative experiments

There is considerable interest in the use of PAEDs in engineering practice. They can be used for several purposes, for instance treating water to remove organic chemical impurities, as acoustic sources in medical or sonar applications, selective separation of solids or plasma blasting in the mining industry. In plasma blasting, there are two different technologies: the first one consists of placing the electrodes directly on the rock. The electrical arc is generated inside the rock. It produces a spall and drilling consists of generating successive spalls. The second technology involves generating the electrical arc in a liquid. The electrical discharge induces a shock wave, which is subsequently transmitted to the rock.

As we will see in the following chapters, the load applied to the rock in the proximity of the drilling site is a pressure wave generated by an electrical discharge between two electrodes placed in a wellbore filled with water. The amplitude of this pressure wave can reach up to 200 MPa, while its duration is about 100 microseconds. This pressure wave is transmitted to the rock by the fluid inside the wellbore, and creates microcracks of decreasing density with increasing the distance from the well.

In order to study the feasibility of PAEDs for fracturing rocks, preliminary experiments have been carried out [MAU 10]. The objective was to investigate the experimental correlation between cracking and damage due to a compression shock wave with the intrinsic permeability of the material and with its microstructure characteristics. The wave was generated under water and then transmitted to a cylindrical specimen 100 mm diameter and 125 mm in height (see Figure I.1). The amplitude of the compressive shock wave was prescribed by the amount of energy that is involved in the PAED. Microcracking and compression damage were due to local extensions induced by the Poisson's effect developed in the course of loading. Single and repeated shocks were considered.

out-coming fluid flow was outside the range of the flow-meters used. The data point for 10 shocks is probably an underestimation of the average permeability (since it is much higher when the specimen is cracked).

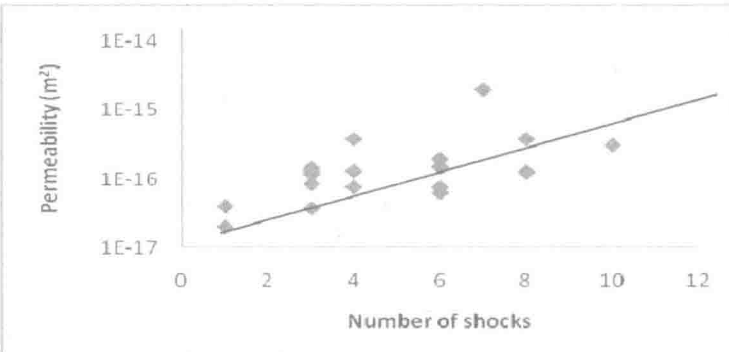

Figure I.3. *Evolution of permeability with the number of shocks, under a peak pressure equal to 90 MPa*

These data clearly show that the foreseen principles of electrohydraulic fracturing are correct and that the technique deserves some close scrutiny. In the following chapters, we are going to investigate electrohydraulic fracturing. In Chapter 1, we will start with the description of experiments that are more representative of the actual state of stress of typical formations containing gas, and of the process used in order to produce the electrical discharge. Chapter 2 will be devoted to the theoretical and numerical modeling of the process. In Chapter 3, we will perform the calculations of the experiments and examine the validity of the computational model. Chapter 4 is devoted to computations on representative configurations and directions for the optimization of the process.

Most of the work performed in the following relies on experiments performed on model materials designed in order to mimic tight rocks. A cement-based mortar has been developed for this purpose, with elastic and hydraulic development that are quite similar to tight rocks. The development of this mortar was indeed necessary in view of the large number of experiments, which were performed prior to achieving a reliable testing procedure, and also to obtain first experimental data on which theoretical models were developed and validated.

Contents

1

Experiments in a Representative Environment

The experimental program presented in this chapter included several distinct phases:

– mechanical experiments in which specimens were subjected to representative confinement stresses and to pulsed arc electrohydraulic discharges (PAEDs);

– permeability tests performed before and after the mechanical experiments in order to quantify the increase in permeability upon electrohydraulic fracturing;

– X-ray scanning tomography before and after the mechanical experiments in order to visualize the crack network generated by the mechanical loads.

We are going to detail the experiments and discuss the results obtained on a model material (mortar), and on sandstone.

1.1. Mechanical set-up

Our aim is to design experiments that implement conditions that are that are as close as possible to real ones.