1 Introduction

1.1 Motivations and Objectives

Energy demand of the world is undergoing a process of rapid growth. From 1991 to 2016, total world energy consumption had increased by about 60% [1]. Even in nowadays scenario, i.e. due to the improvement in the efficiency of the energy intensity by 2015 was more than 30% lower than that in 1992 [2], the total consumption will still expand by 30% until 2040, equivalent to add another China and India to today's global demand [3].

Since the beginning of the 21st century, many countries and organizations have proposed that human beings should vigorously develop the renewable energy. This is on one hand to ensure its own energy security, and on the other hand sustainable development can also be maintained. However, although countries have increased their investment in renewable energy, compared with the original plan, the nowadays' schedule has been greatly delayed. As a result, fossil energy will remain an important pillar of the world's energy system for the foreseeable future. In the projection of EIA in 2016 [4] (Fig. 1.1), fossil fuels will still account for 78% of the world's energy consumption until 2040 [5], especially in the non-OECD countries.

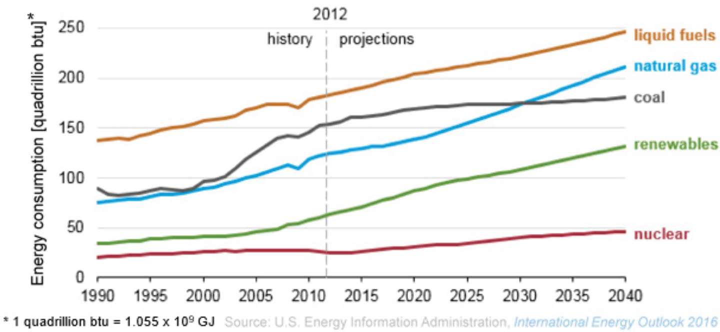

Figure 1.1 World energy consumption by source, 1990–2040 [4]

Based on this situation, reservoir stimulation once again becomes a very important operation not only in petroleum industry but also in geothermal exploitation. Since most of the new proven gas/oil reserves are unconventional reservoirs, i.e. tight and the deep geothermal reservoirs, they both have the characteristic that the involved permeability is too small to provide an economical production (the permeability of a tight gas reservoir is usually smaller than 0.1mD). In order to create artificial conductive channel or to enhance the conductivity of natural fracture, stimulation operations have become essential (Fig. 1.2). However, although the reservoir stimulation techniques represented by hydraulic fracturing has been developed since 1940s, the related scientific research is still only a matter of recent decades. Relying on the rapid development of computer science in the past 30 years, now it becomes possible to use numerical simulations to conduct detailed pre- or post-production studies on the fracturing process. As a result, a large number of numerical simulators have emerged in industrial and research fields.

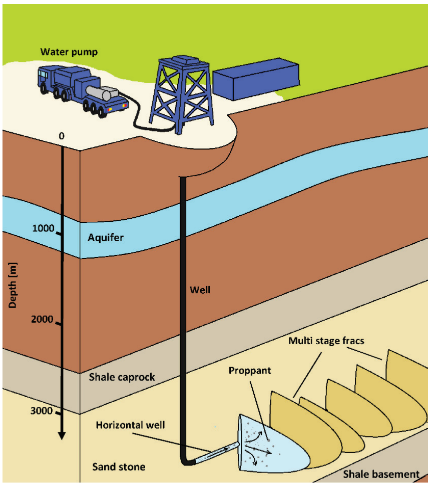

Figure 1.2 Demonstration of the stimulation operation in tight gas reservoir

Although commercial simulators such as FracPro and MFrac can generally provide a good reference to the fracturing's results, however, these simulators are still too simplistic for researchers who want to achieve further improvements in the fracturing methods. For example, in MFrac of Baker Hughes, developers adopted several classical models such as PKG and KGD to perform the simulation. In this way, although these models can provide a fast semi-analytical solution, but the resulted fracture always possesses a fixed form. For this reason, some research groups have developed their own simulation codes.

1.2 Background

Prof. Hou's team believes that combining the most advantageous simulators in different fields (especially those simulators that can simulate physical processes at engineering scales.) with servo codes to obtain their capabilities in corresponding areas, will be the best solution for the above mentioned problems. Based on this idea, after several years of development, the team has developed two sets of simulation codes named FLAC3D^{plus} and TOUGH2MP-FLAC3D.

Among them, FLAC3D^{plus} mainly utilizes the features of FLAC3D in geo-mechanics. On this basis, by further developing the calculation program for fluid flow (within main fracture and porous rock formations) and proppant transport, the set of code has finally obtained complete ability to simulate hydraulic fracturing in the tight sandstone (dominated by tensile fracture perpendicular to the minimum principal stress). TOUGH2MP-FLAC3D provides the calculation of hydraulic and thermal fields to TOUGH2MP while transferring the geomechanical calculation to FLAC3D. The advantage of this coupling is that as the thermal and hydraulic calculations performed by TOUGH2MP can be more complex, FLAC3D can also perform its ability to simulate the mechanical behavior of rocks other than tight sandstone. However, this simulator cannot model the transport of solid proppant.

1.3 Thesis outline

In this thesis, several numerical studies focusing on reservoir stimulations in tight sandstone and deep geothermal reservoirs were carried out. Using FLAC3D^{plus} and

TOUGH2MP-FLAC3D, corresponding modeling involving hydro-mechanical (HM) or thermo-hydro-mechanical (THM) couplings have were performed.

In order to narrative the research work more clearly, the theoretical background or rather governing equations for describing the thermal, hydraulic and mechanical processes will firstly be introduced in Chapter 2.

Chapter 3 conducts a systematical study of the influences from fluid's viscosity on the fracturing results. Using the improved thermal module, which gains the ability to model thermal effects on fluid's properties, several important phenomena that reflect the interactions between fluid viscosity, development of fractures and rock formations have been analyzed. After considering the fluid's ability to carry solid proppant and depending on a real case study of the Leer, several recommendations to improve the results have been proposed.

Chapter 4 illustrates a research work for the EGS (Enhanced Geothermal System) project Landau. This study aims to analyze the relationship between reservoir stimulation and induced seismicity. In order to rationalize the granite's gradual loss of strength during the failure process, the concept of damage was also introduced. Relying on various modified treatment schedules, suggestions and countermeasures for dealing with induced seismicity have been explained at the end of study.

To further enhance the functionality of FLAC3D^{plus}, Chapter 5 proposes the improvement from the perspective of geometry. After implementing the modified codes into the simulator, two verifications and one 3D example have been presented in order to demonstrate the new features of this powerful simulator.

2 Fundamentals for describing the reservoir stimulation in a geosystem

2.1 Overview of a reservoir stimulation and the corresponding geo-processes

Reservoir stimulation is a very important activity of the production engineer in the modern petroleum and related industries (such as geothermal). Its main purpose is to obtain a faster delivery of the oil/gas [6] from the reservoir to the wellbore or an increased heat exchange area of the medium. Thus the working efficiency of the production system can be increased and consequently the ultimate economic recovery can be enhanced.

In recent years, by utilizing the application of reservoir stimulation in various unconventional oil/gas exploitation (tight oil/gas, shale oil/gas, etc.), through horizontal well-based multi-stage matrix stimulation and hydraulic fracturing, the connection of the wellbore with the reservoir has been greatly improved (Fig. 2.1). Such improvements, on the one hand, enable the oil/gas to be released from the tight reservoir and quickly reach towards wellbore, and on the other hand the need for another important activity, i.e. artificial lift, is delayed.

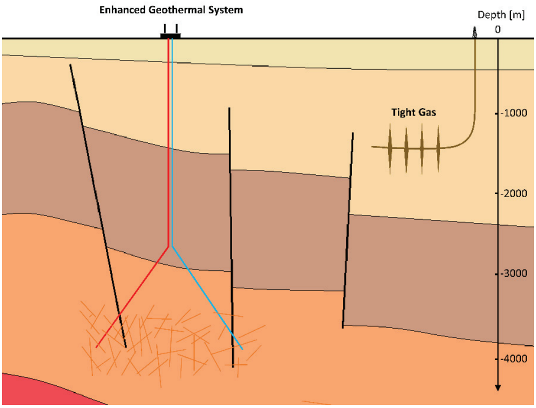

Figure 2.1 Reservoir stimulations in a subsurface geosystem

Another exploitation activity that possesses a high demand for the reservoir stimulation is the development of Hot Dry Rock (HDR) geothermal energy, which is also called the Enhanced Geothermal System (EGS) (Fig. 2.1). Since the high-temperature rock mass in an EGS is mainly located in the underground of several kilometers and is tight and impermeable, the pressurized water can not only make many hydraulic fractures perpendicular to the direction of the minimum principal stress, but can also enable some small natural joints in the rock mass to be expanded into larger ones. In this way, by increasing the contact area, the thermal energy contained in the underground hot rock can be extracted by the heat exchange medium more effectively.

Since all the main processes of reservoir stimulation occur in the underground, the various geo-processes in the subsurface geosystem during or after an operation have become focuses of the research. In the depth of the formations where reservoir stimulation carries out, solid rocks form the main support structure [5]. As the rocks are primarily porous media made of various mineral grains and cementations, after many tectogenesis, volcanic activities and weathering, natural cracks are generated in most rocks and in large scales even form several faults. Therefore, from the perspective of the integrity, the rocks can be classified into the intact rocks without fractures and fractured rock mass with fractures. In this large number of intact rock and fractured rock masses, the introduction of reservoir stimulation leads to many additional processes that are more dramatic than natural processes. Depending on their different principles, both natural and additional/induced processes can be classified into several different categories, such as thermal (T), hydraulic (H), mechanical (M) and chemical (C) processes. Although these processes are independent of each other in terms of principle, they will interact with each other during actual execution, e.g. the fluid flow in the fracture also causes the heat transport, and the contact of the low temperature fluid with the high temperature rock mass will lead to thermal contraction of the solid body. Such effects are referred to as mutual coupling as well, and Figure 2.2 is a schematic representation of such coupling effects. In order to better understand and describe these processes and their coupling effects, in this chapter, the governing equations of the individual processes involved in a reservoir stimulation (except chemical processes) will be introduced.

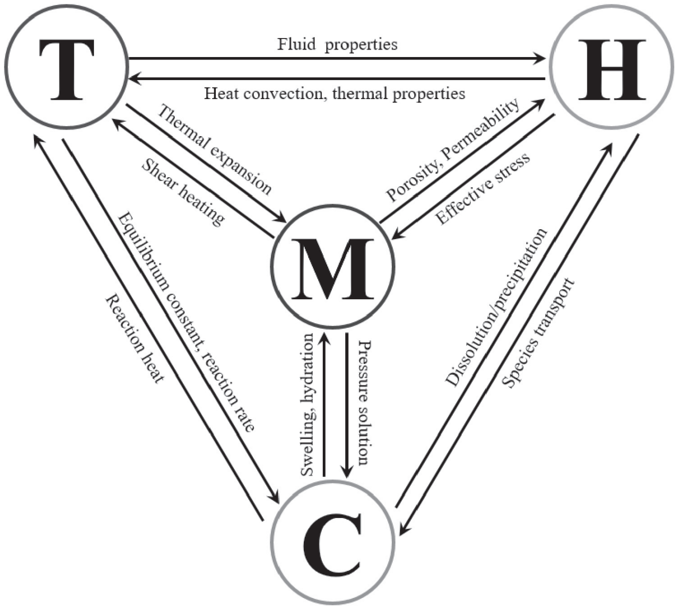

Figure 2.2 Overview of the coupled THM/C processes in a reservoir stimulation [5]

2.2 Geomechanics in the reservoir stimulation

Describing the geomechanics in a reservoir stimulation is actually very complicated. Since many different mechanical processes appear in an operation, the corresponding governing equations will be numerous. For example, the linear poro-elasticity theory can be used to describe the rock's deformation due to the change of fluid pressure but the fracture propagation can usually only be determined by using elastic or plastic fracture mechanics. Despite of this, analysis of the geomechnical problems is mainly considered by three conditions, namely the equilibrium, the continues and the physics [7].

2.2.1 Stresses and forces equilibrium

The study of the classical mechanics focuses on the position of a body and its two time derivatives, namely the velocity and the acceleration. In order to quantify the interaction of a given body with other objects, the forces that other objects apply on the body must be analyzed. These effects of forces applied on the body are described by Newton's law of motion. This law states that the sum of the forces acting on a body is equal to the mass of the body times its acceleration, i.e. when the sum of the external forces and moments acting on the body is null, the body will be in an equilibrium state.

The basic mechanical concepts given above can also be applied to the deformable bodies such as rock masses. However, in rock mechanics, the analysis methods must be slightly altered for various reasons: first, the force applied to a rock will, in general, vary from point to point, i.e. distribution of the force over the body must be taken into account; second, the idealization that forces act at localized points is not sufficiently general to apply to all problems encountered in rock mechanics [8]. Hence, Cauchy proposed the continuum mechanics and gave the definition of stress and strain in 19th century (Eq. (2.1)). The stress, which is also called traction, is defined as the force acting on an infinitesimal area (Fig. 2.3). Since the traction generally varies with the orientation of the surface on which it acts, the most convenient way for its representation is by means of an entity known as stress tensor.

$$\vec{\sigma} = \lim_{\Delta S \to 0} \frac{\Delta \vec{F}}{\Delta S} \tag{2.1}$$

Where $\vec{\sigma}$ is the stress vector [Pa], $\Delta\vec{F}$ is the vector of the internal force [N], ΔS is the corresponding area to the internal force [m^2].

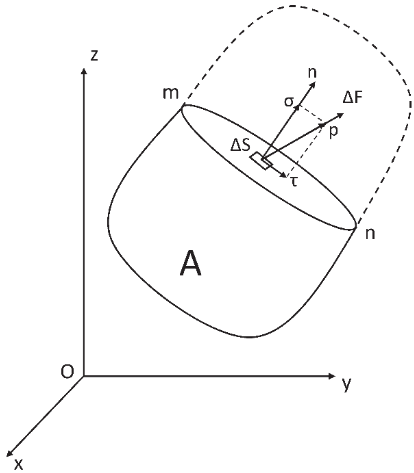

Figure 2.3 Schematics of the stress

2.2.1.1 Cauchy's stress tensor

In order to derive the Cauchy's stress tensor, first consider division of the internal force into one normal and two shear directions of a surface, therefore, one normal and two shear stresses are obtained (Fig. 2.4 (a)). Extending the same idea to the planes perpendicular to the three axes of a Cartesian coordinate system, yields three normal stresses (σ_{xx}, σ_{yy}, σ_{zz}) and six shear stresses (τ_{xy}, τ_{yz}, τ_{zx}, τ_{xz}, τ_{zy}, τ_{yx}). From this, the stress state of a point in a Cartesian coordinate system can be described through all these decomposed stresses (Fig. 2.4 (b)).

$$T_j^{(n)} = \alpha_{ni}\sigma_{ij} \tag{2.2}$$

Where $T_j^{(n)}$ is the component of the stress vector $\overrightarrow{T^{(n)}}$ on section ABC in j-direction [Pa], j = x, y, z, α_{ni} is the cosine between normal of the plane and three Cartesian coordinate axes [-], i = x, y, z, $\alpha_{n1} = \cos(n, x)$, $\alpha_{n2} = \cos(n, y)$, $\alpha_{n3} = \cos(n, z)$, σ_{ij} is the components of the stress vector above the section i (BOC, AOC, AOB) on three axes, i, j = x, y, z.