Design Process of Adjustable Stress and Heat Cell for Hydraulic Fracturing Reservoir Engineering Applications

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ABSTRACT

The success of reservoir creating applications in hot dry rocks have been related to many factors. Simulation and laboratory tests are important both for minimizing risk factors and time. Also, it is important for minimizing investment and operating expenses. For such a laboratory work, there is a need for a simulation cell that can simulate the temperature and pressure in three different axes, while also allowing fracturing activities in it. The aim of this study is to make a CAD design of a true triaxial stress and heat simulation cell which will allow the application of the hydraulic fracturing method under the true underground conditions and also to make CAE analysis of this CAD design in computer environment. This cell is designed to be compatible with many additional devices because it forms the heart of a hydraulic fracturing simulation laboratory. Hydraulic fracturing pump, acoustic gap analysis system, fracturing fluid mixing tank, and permeability testing device will be developed with this device. They will be designed to communicate with each other via protocols such as sensors and profinet to decide instantaneously the best liquid pumping speed and mixture in the current conditions. The cell has changeable plates. In this way, it can accept samples from 10 cm to 40 cm in each axis. The hydraulic cylinders to provide this dimensional width have a capacity of 200 tons and high strokes like 20 cm. The design parameters of this device are, to apply pressure up to 150 MPa and to apply temperature up to 200°C to rock samples which have changing dimensions from (10x10x10) cm³ to (40x40x40) cm³ and finally to perform a hydraulic fracturing application over these samples under these conditions. There have been made many CAD designs and CAE analysis to realize a design which can achieve these design parameters. In CAE analyzes, the deformations and stresses that the current model was subjected to under various pressure conditions were examined by the finite element method. The results obtained from these analyzes are presented as “Total Deformation” and “Von-mises” Stress Criteria.

1. INTRODUCTION

Both HDR and EGS systems have a great potential all over the world. Turkey also has a great potential for possible HDR and EGS geothermal systems. We can say this as a result of the geological and geophysical research on Turkey. Turkey has all the geological conditions expect continental rift which are Plate borders, shell thinning places, surrounding stratovolcanoes, Granites and Deep Roots, Radioactive Decay (Burçak,2011). Some of the detailed research show that HDR and EGS potential for 3-5 km in Turkey is significant. The total EGS-Enhanced Geothermal System technical and economical electricity production potential of Turkey (3-5 km) is 250.000 MWe (20 US $ cent/kWh) (Mertoğlu,2015). Although Turkey has a great potential for both EGS and HDR geothermal systems, there is no HDR nor EGS studies for reservoir engineering studies on the field. Even there is no laboratory or facility to develop or to test for reservoir engineering applications on the hot dry rocks and enhanced geothermal systems.

For this reason, we have started a project about 3 years ago to develop a laboratory to test hydraulic fracturing equipment and liquids on the rocks under underground conditions. There are some examples for these types of laboratories on the world. Although some companies sell some equipment for this kind of laboratories and studies, scientists prefer to develop and manufacture their own test equipment for the reason of the special test conditions that they have planned to test on rocks.

Underground stress and heat simulation is essential for a laboratory like this. To simulate these conditions, Luke P. Frash, Marte Gutierrez and Jesse Hampton have developed a true triaxial test apparatus that can apply confining stresses up to 13MPa in each three axis and can heat sample up to 180°C degrees (Frash et al.,2014). Also, another essential equipment for a study like this is a fracturing pump. Frash and others have been used a hydraulic syringe pump that has been produced by Teledyne Isco, and model 65 DM (Frash et al.,2014). They have a fixed sample size of (30x30x30) cm³ for this triaxial stress cell. Design process of this equipment needs some CAD and CAE study on computer and paper. Guang-Qing Zhang, Tiegang Fan have used Solidworks to design their stress cell (Zhang and Fan, 2013). We have designed our CAD model with Autodesk Inventor, and after we have satisfied with work progress of CAD model, then we have made finite element analysis on our CAD model with ANSYS. Our progress on stress and heat cell has been finished and we have start to produce the cell in our workshop. CAD design progress is still on going for other equipment.

2. LABORATORY SETUP AND EQUIPMENT

In this study we have planned to build a hydraulic fracturing simulation laboratory. For this Laboratory four core machines have been designed in the beginning. These machines will allow researchers to test hydraulic fracturing capabilities of Turkey’s reservoir rocks and also researchers can test new fracturing pumps, new liquid mixes and new scenarios for fracturing with this laboratory setup. A PLC controlled hydraulic fracturing pump a true triaxial stress and heating cell, an electronic controlled mixing and dosing machine, a permeability test equipment and after those machines, a gap detection system have been designed for this laboratory.
Hydraulic fracturing pump has been designed to pump a liquid mixture into a sample in the triaxial stress cell. Pump will have a HMI screen that can allow to change the different loading scenarios like continuous and pulsed loading. Also pump loading speed will be adjusted from HMI screen.

True triaxial stress and heat cell can accept samples form \((10\times10\times10)\) cm\(^3\) to \((40\times40\times40)\) cm\(^3\) with the help of its changeable plates. The cell can heat samples up to 200°C and also it has a capacity of loading 200 tons in three different axes. A patent is pending for this machine.

Figure 1: True Triaxial Stress and Heating Cell and hydraulic fracturing pump

Fracturing liquids are important both to start a fracture and to keep this fracture open. Different rocks need different liquid mixtures. A mixture and dosing machine has been designed to prepare fracturing liquids. Electronic control will allow to mix four different materials and liquids in different doses.

The main aim of a hydraulic fracturing application is to develop a fracture system in a solid rock like a granite. In this way this rock becomes a reservoir that can allow liquid circulation and heat transfer in it. A permeability test equipment has been designed for \((20\times20\times20)\) cm\(^3\) rock samples that researchers can compare the liquid circulation gap before and after the hydraulic fracturing applications. We are planning to measure water penetration in a fixed time period through a rock sample in an isolated cell before and after hydraulic fracturing.
Figure 2: Permeability test equipment

Permeability test equipment has been designed to hold (20x20x20) cm³ rock samples in it. Test procedure for permeability is to compare the liquid passage amount from a rock sample before hydraulic fracturing and after the hydraulic fracturing. The main aim of this machine is to measure volumetric gap change and to see the efficiency of hydraulic fracturing method in a way. First a rock without any deformation will be placed in this test equipment. Test equipment will have a water depo on it and there will be a piston with a fixed weight in this depo. There will be a vane at the end of this water depo. At the end of the vane there will be a sealed contact plate for contacting the surface of the rock sample. There will be an empty water depo at the bottom contact of the rock surface. For a fixed time like one hour and under a fixed force like 5 kgs on the top of the water depo, the passing liquid inside the rock sample will be measured. This procedure will be repeated after the hydraulic fracturing process and gap occurrence will be compared under different hydraulic fracturing conditions.

Also, an acoustic emission equipment will be added to detect sensitive fissure creation in real time. At this moment monitoring the crack and fissure occurrence will happen with monitoring pressure change of the pumping liquid.

Figure 3: Laboratory Setup
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IOT (internet of things) communication network is under development between dosing machine, hydraulic syringe pump, and overall control software in a laptop. A communication protocol will be established between tree different types of machine to acquire right liquid mixture and right pumping speed and method instantly according to the change in pressure and acoustic emission data. The aim of this communication is to get more controlled cracks in a reservoir. A control software and an algorithm will be developed for the coordination of the machines. This software will make decision to crack the rock more effectively. The main bridge between equipment will be Siemens IOT2020 unit. Other control units on machines will be a siemens plc and a raspberry pi. Different software languages will be used on different machines. Main control unit will be programmed by C#.

3. CAD PROSSES OF TRIAXIAL STRESS CELL

The mean aim of this machine is to apply loads on rock samples in each axis and also to apply heat on rock samples up to 200 degrees Celsius. In this way, machine can simulate the underground conditions like triaxial stresses and heat. Right simulation of the stresses and the heat is critically important for a simulation of hydraulic fracturing application in a laboratory environment.

The most specific feature of this machine is its changeable plates. With the help of this changeable plates, machine can accept (10x10x10) cm$^3$ to (40x40x40) cm$^3$ sample in it. In this way researchers can select different sized rectangular samples to test. This machine can apply up to 200 tons of load on every axis independently.

![Figure 4: Inside of cell and frame of the machine](image)

True triaxial stress and heat cell can be divided into three different structures. These are steel profile frame, inner cell, and pressing plates with hydraulic cylinders. NPU 200 Profiles have been chosen to build the frame. All the connections on this frame have been made with MIG welding. Fifty millimeter thick structural steel plates which have 250 MPa yield strength have been used to build inner cell walls. To prevent welding errors on cell, bolted connections have been used on cell. After the montage of the moving parts and the cylinders, welding will be applied on the required sections of the cell. The plate and cylindrical supports of the plates that connect plates to cylinders will be made from C45 steel because the pressure and heat on that section will be very high. C45 has 580 MPa yield strength.

4. FEM ANALYSIS OF THE CELL

After the mechanical design of the cell has been finished, the finite element analysis has been stared. The aim of the finite element analysis is to determine the strength of the cell under the loads that we will apply in laboratory tests. We have used ANSYS software to analyze structural strength off the cell.

We have tested several loading models like adding loads directly on plates and frame. Adding loads on frame and plates have not represented the real scenario in the real world. So, we have tried to make the most realistic scenario for this triaxial stress cell. Thus, we have designed a real moving cylindrical piston in a cylinder gap, and we have added the 45 MPa pressure inside the cylinder gap in three axes. Loading time of the pressure has been taken one second.

In this way, the main source of the stress over the cell has been represented very close to real world. Pressure inside the gap has moved the cylinder piston, and piston applies pressure over granite sample, and granite transmits the pressure to other parts of the cell.
Figure 5: Figure 4. Pressure inside the cylinder

Materials used in FEM analysis in ANSYS are structural steel and c45e steel. NPU 200 profiles and 50 mm steel plates are modelled as structural steel material. Steel plates and circular steel parts inside the cell are modelled as c45 steel material.

Table 1. Material properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm³)</th>
<th>Young modulus (GPa)</th>
<th>Passion ratio</th>
<th>Bulk modulus (GPa)</th>
<th>Shear modulus (MPa)</th>
<th>Tensile yield strength (MPa)</th>
<th>Tensile ultimate strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural steel</td>
<td>7.85</td>
<td>200</td>
<td>0.3</td>
<td>166</td>
<td>76923</td>
<td>250</td>
<td>460</td>
</tr>
<tr>
<td>C45 steel</td>
<td>7.8</td>
<td>210</td>
<td>0.28</td>
<td>159</td>
<td>82031</td>
<td>580</td>
<td>810</td>
</tr>
</tbody>
</table>

Rock sample has been represented as a rigid cube and its material has been chosen as C45 steel. In this FEM analysis, rock sample deformation has not been modeled. The aim of the FEM analysis in this study is to design an underground stress cell which can endure the pressures near 45 MPa from tree axis.

The connections in the analysis have been chosen as welded except the cylinder piston and cylinder gap. These connections have chosen frictionless. And supports for the cell were taken from bottom of the profiles.

The meshing setting for triangle surface mesher is program controlled. There have been 1144928 nodes and 602852 elements used for this meshing.

There have been used fixed supports and these supports have been taken at the bottom of the triaxial stress cell where it has been contacted with ground. There have been eleven contact faces of triaxial stress cell.

Figure 6: ANSYS analysis (Total deformation)
Figure 7: ANSYS analysis side section (total deformation)

Figure 8: ANSYS analysis stripped side section (total deformation)

Figure 9: ANSYS analysis (von-mises)

5. RESULTS
Total deformation analysis generally shows that there will be a deformation under the full load. This deformation is about 0.86 mm and in the cylinder pistons at the horizontal axis. Stresses on frame generally concentrate on the piston plate connections. Total deformation analysis shows that stresses on the horizontal axis are more than on vertical axis.
According to Von-mises stress analysis, there is not any plastic deformation on stress cell. True triaxial stress cell is in the safe zone for yield strength.

After the production of the real triaxial stress cell, these analyses and this load model will be tested.

* The CAD cell model (as machine) seems to be complete. Nevertheless, it is not clear how the sample (rock) is modelled. The paper neither expose clearly the type of materials defined for the computational model (This is an input data of ANSYS) nor the type of element used (i.e., tetrahedro, prisma, etc). The paper do not explain the number of total elements resulting from the meshing/gridding process. Please kindly add all this key information to the paper.

A section has been added which describes the material properties and the meshing properties of the ansys analysis into fourth section.

* In the Introduction section it is described that the paper will develop a hydraulic fracture modelling. Nevertheless, no hydraulic fracture analysis is presented throughout the article. Please add the analysis or edit the Introduction.

Hydraulic fracture modelling of a rock example is one of targets of our laboratory but this paper explains the laboratory setup, its functions and properties especially the three axial stress cell which will simulate the underground heat and three axial stresses.

*In the Results section, it is concluded that there is no plastic deformation in the cell, but there is no previous description of the material model defined for carrying out the finite element analysis. Please elaborate on this.

Modeling and material details have been added to FEM section of the paper.

* The paper mentions: “We are planning to measure water penetration in a fixed time period through a rock sample in an isolated cell before and after hydraulic fracturing.”. Nevertheless, there are neither comment on how the finite elements model will be validated using this data, nor on how the hydraulic fracture model will be built (for instance, how the fault line would be determined or how the fracture geometry would be modeled throughout time). Please elaborate more on this.

Detailed information about water penetration measurement has been added into paper and also drawing of permeability test equipment has been added to paper. For now FEM analysis is only to determine triaxial stress cell and its structural strength. After the establishment of this laboratory we will examine hydraulic fracture occurrence under different conditions with different liquids and pressure application regimes after that we will try to make a hydraulic fracturing occurrence prediction model using different methods. FEM method can be method for this prediction model but we didn’t decide it yet.

*The fact of considering a triaxial load system does not make the simulation model more reliable. The study is neither presenting the analysis foundation neither the validation methodology that would be used. Please elaborate on this.

Aim of the triaxial stress cell is to simulate the underground three axial situation. According to studies about hydraulic fracturing applications both in situ and in laboratory there are tree main forces which effect to hydraulic fracturing (the most well known study about this phenomenon is “mechanics of hydraulic fracturing” Hubert and Wills in 1957. Also there are test equipment designs like ours to simulate underground conditions, for example Frashn L.P., Gutierrez M., Hampton J. has been designed and produce a triaxial test equipment like us in a study “True-triangular apparatus for simulation of hydraulically fractured multi-borehole hot dry rock reservoirs”.

For the model of the forces that effects on triaxial stress cell, we have decided to simulate them in hydraulic cylinders as pressure and we have modeled cylinder piston as a directional moving part in one axis for every cylinder. This connection has been established as frictionless. This is the closest model to real situation because cylinders move like this. By the way validation of this model will be realized after production of the triaxial stress cell. We are planning that as a different and further study.

* The paper seems to describe more extensively the CAD design (pieces, shapes, and volumes) than the finite elements design and analysis (which is not the same as the CAD design). Please improve the description of the finite elements design.

Two new figures about the inside deformation has been added to show more detail about where the most deformation occurs and its structure. Materials, mesh, support and pressure loading time details have been added to FEM analysis section.

* The article objective needs to be reviewed and the missing information needs to be completed or the article scope needs to be redefined.

REFERENCES


