Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Thermal Stress Mitigation Testing of Externally Cemented Flexible Coupling in Geothermal Steam

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Keywords: Casing, failure mitigation, cement integrity, modeling, flexible couplings, in-situ testing

ABSTRACT

Casing failures in-high temperature geothermal wells occur if the casing is overstressed. The most common failures occur because of axial forces and/or differential pressures. For medium-enthalpy geothermal wells, thermal cycling has the potential to severely deteriorate the integrity of the cemented annulus and for higher enthalpy wells yielding of casings becomes a structural concern. The recently innovated patent solution, flexible couplings, aims to reduce thermal straining by allowing displacement into the connections of each casing segment at approximately 12 m intervals (API R3). In the GEOTHERMICA internationally co-funded GeConnect project a full-scale experiment is performed at a well site in a high-temperature geothermal field. The experimental set-up is composed of two concentric casings cemented together and the inner one equipped with a flexible coupling. The aim is to investigate effects of thermal cycling on well integrity and to test the function of cemented-in flexible couplings using a bypass of a producing well. Cement sheath integrity and cement-casing boundary are evaluated at moderate to high temperatures, e.g. by using fiber optic distributed sensing technology. Structural models are used to analyze casing-cement interactions and to evaluate prospects and potential improvements of well integrity by using the new technology of flexible couplings.

1. INTRODUCTION

In the GeConnect project the recently patented technical solution of flexible couplings, intended for casings in geothermal wells, is tested in a surface experiment where a casing section including a flexible coupling will be cemented in to simulate the downhole structure. The flexible coupling connections are designed to relieve stresses that form during heating by allowing small axial movement of the casing into the connection. Conventional casing connections are static, thus during initial thermal recovery of wells stresses can exceed the material strength of the casings resulting in permanent deformations (plastic strain). Such permanent straining of the material can lead to tensile failures if wells are allowed to cool down again from the hot discharge state, e.g. if shut-in or cooled during workovers (Kaldal, et al., 2016). The primary goal of flexible couplings is to reduce probability of such permanent deformations. The cost of geothermal wells for co-generation of electricity and district heating system is typically 20-50% of the total investment cost of the energy production (Pálsson, 2017). Frequent failure mechanisms in high-temperature geothermal wells are casing collapse and mechanical overload of the casing string in the well due to constrained thermal expansion (Lohne, et al., 2017) (Thorbjornsson, et al., 2019). In addition, for medium enthalpy geothermal wells, temperature and pressure cycles above 100°C during construction, operation and shut-in phases have the potential to severely deteriorate the integrity of the cemented annulus (Ter Heege, et al., 2017).



Figure 1: Patented solution of flexible couplings and two built prototypes for 9 5/8″ casings (Thorbjörnsson, et al., 2017).

The goal in the GeConnect project is to test new technology that aims at increasing the reliability of the downhole construction of geothermal wells beyond the state of the art, i.e. flexible couplings, that were developed in EU Horizon 2020 projects GeoWell (grant agreement No 654497) and DEEPEGS (grant agreement No 690771) and fiber optic distributed strain sensing technology successfully tested in EC funded project GeoWell (Raab, et al., 2019) (Lipus, et al., 2018) (Reinsch, et al., 2019). Using the technology in the surface experiment, cement sheath integrity and the cement-metal interface will be evaluated. Steam from a high-temperature geothermal well is used to induce thermal cycling loads, first at moderate temperatures at atmospheric conditions (~100°C) and then at higher temperatures at wellhead conditions (250-300°C). The resulting strains and displacements will be monitored throughout the test and compared to numerical model results.

Full-scale prototypes of the flexible coupling have already been laboratory tested in GeoWell at ambient temperatures (Ragnarsson, et al., 2018). For the full-scale experiment in GeConnect, a prototype for 9⅝″ casing will be tested in geothermal environment by feeding steam directly form a high-temperature geothermal well through the test setup. The objective is to validate the function of cemented in flexible couplings at elevated temperatures and to monitor the casing-cement bond integrity by monitoring strains/displacements, with fiber optic distributed strain sensing technology complemented by high-temperature strain gauges and conventional acoustic sensors. Possible implications and risks associated with using the new flexible couplings are assessed through structural modeling of the surface test, upscaling to field-scale and by performing a quantitative risk assessment analysis. Structural analysis will be used to evaluate the performance of flexible couplings and analyze the potential benefits of reducing thermal axial stress and strain in casings.

2. THE FLEXIBLE COUPLING

Since first work was initiated in the year 2015, the flexible coupling has evolved from a concept to a tested and patented solution (Thorbjörnsson, 2017). The objective of the flexible coupling is to lower thermal stresses in production casings of geothermal wells, increasing reliability and reducing risk of casing failures. Testing its performance in operational conditions at elevated temperatures in the GeConnect project will further establish confidence in its function for use in production casings of future geothermal wells. The flexible coupling was first introduced in the GeoWell project where several full-scale prototypes were developed (Figure 1) and tested (Figure 2). The sliding function of the connection and its structural limits were evaluated, first by finite-element modeling and then in two full-scale testing facilities (Figure 2). The results from these tests that were conducted at ambient temperatures are described by Thorbjornsson et al. (2019) and Thorbjörnsson & Kaldal (2020). The connection was further developed in the DEEPEGS project and has been incorporated in well designs for the Krafla Magma Testbed (KMT) that aims towards better understanding of magmatic systems by establishing the first magma observatory (Eichelberger, et al., 2018) (Hólmgeirsson, et al., 2018). In DEEPEGS, the connection will be built for a 13 3/8″ production casing and put for the first time into use in a high-temperature geothermal well in Iceland (Thorbjörnsson & Kaldal, 2020).

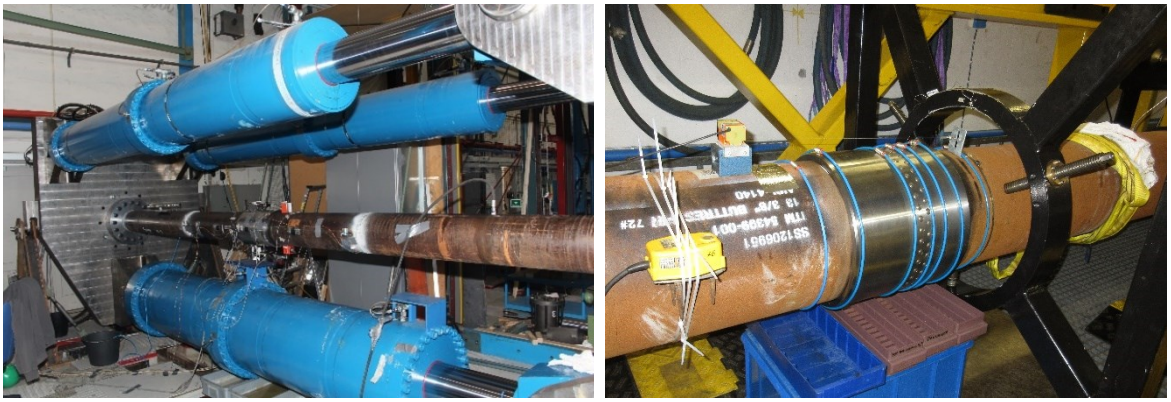


Figure 2: The function and structural capacity of prototypes of the flexible coupling has been tested at ambient temperatures at SINTEF (left) and later after modifications it was tested at NORCE (right) in the GeoWell project. Pictures taken during testing of a 9 5/8″ connection (left) and a 13 3/8″ connection (right).

3. SURFACE EXPERIMENT

The integrity of the cemented annulus and casing using flexible couplings will be tested in a full-scale surface experiment (Figure 3). The experimental setup is made of two concentric casings, the inner one including a flexible coupling and a test frame that is designed to take up the full axial loading of thermally expanding casing. The fiber, used for distributed temperature and strain monitoring, will be glued onto the external surface of the casing. After the casings have been fitted in the test frame, the annulus is cemented with class G cement grout that is typically used for geothermal wells. The diameters of the two casings are 9⅝″ (244,5 mm) and 13⅜″ (339,7 mm). The flexible coupling will be fitted on one end of the inner casing, leaving approximately one casing segment (API 5CT standard range 3) or about 12 m that has the capability to expand axially into the flexible coupling during heating.

Precautions are necessary because essentially, a segment of the well at high temperature and pressure is taken up to the surface. Therefore, the test is designed according to standards for high pressure equipment. The steam that will be used directly from a flowing well is assumed to be at saturated conditions. The test is designed for temperatures of 100°C up to 250-300°C which could reach pressure of 40-85 bar at saturated conditions. Therefore, all components of the test, i.e. experimental setup and flow system, are designed at the appropriate pressure class (ANSI 600-900).

For the experiment to work properly as intended, it is essential to constrain displacements of the end plates. Thermal expansion of the test piece itself is constrained by beams over its whole length, simulating constrained casing-cement-formation system. The test segment will be assembled, cemented and placed at a convenient well pad for performing the surface experiment.

Steam from the geothermal well will be feed through the test setup and the structural response documented for the pre-determined thermal cycles. The pressure/temperature inside the test piece will be controlled with two control valves positioned on each end of the casing. The inflow will be limited and the temperature controlled by back pressure. In the first thermal cycles, the flow of steam will be tempered such that conditions within the casing will be at saturation temperature at near atmospheric pressure. The test piece will then be allowed to cool down to the original temperature. Later, the back-pressure of the casing will be controlled by a control valve, increasing the pressure and temperature to wellhead conditions of the selected well. A productive well with pressure of 40-85 bar-g will be selected to simulate downhole conditions up to a maximum of 250-300°C. By this the wellbore warm-up during initiation of flow will be simulated. Once the test piece has reached near steady-state conditions it will be de-pressurized and quenched by pumping cold water through it. This will simulate worst conditions in a hot well that is killed by water. The flexible coupling is designed to mitigate the axial stresses that the contraction would normally produce in a casing string with conventional connections. This is due to lower strain forming in the casing as it heats up initially.



Figure 3: Experimental setup of a 9⅝″ casing with flexible coupling cemented into a 13⅜″ casing. The test setup is designed to keep ends in fixed position during warm up simulating downhole conditions. As high-temperature steam is feed through the casing, the internal casing expands thermally. The flexible coupling positioned at the end of the internal casing allows the casing to expand when heated up.

4. FIBER OPTIC MONITORING TECHNOLOGY

In order to monitor the thermal expansion of the casing and the operation of the flexible coupling, distributed and quasi distributed fiber optic monitoring technologies will be applied. Along the 12 m casing segment, a little groove will be grinded into the casing. Into this groove, three optical fibers will be glued. One for distributed strain sensing, one for quasi distributed strain sensing based on the Fiber Bragg Grating technology and a third for distributed temperature sensing to allow for temperature compensation of the measured strain values. For distributed strain sensing, we use an Optical Backscatter Reflectometer (OBR 4400 by LUNA Technologies) which is based on Optical Frequency Domain Reflectometry (OFDR). Initial laboratory experiments were performed to test different glues for coupling the optical fiber to a piece of steel. Figure 4 shows initial test results from the OBR 4400 for thermal cycling of a test sample with different types of glue (A – D). The profiles on the right subplot show relative strain changes measured by the fiber when heating the oven from 20 °C to 50 °C. Over the glued intervals (A – D), a higher strain is measured compared to the locations where the fiber is lying freely. The strain measured at the free lying fiber is caused by the temperature effect which needs to be corrected for when calculating the pure deformation.

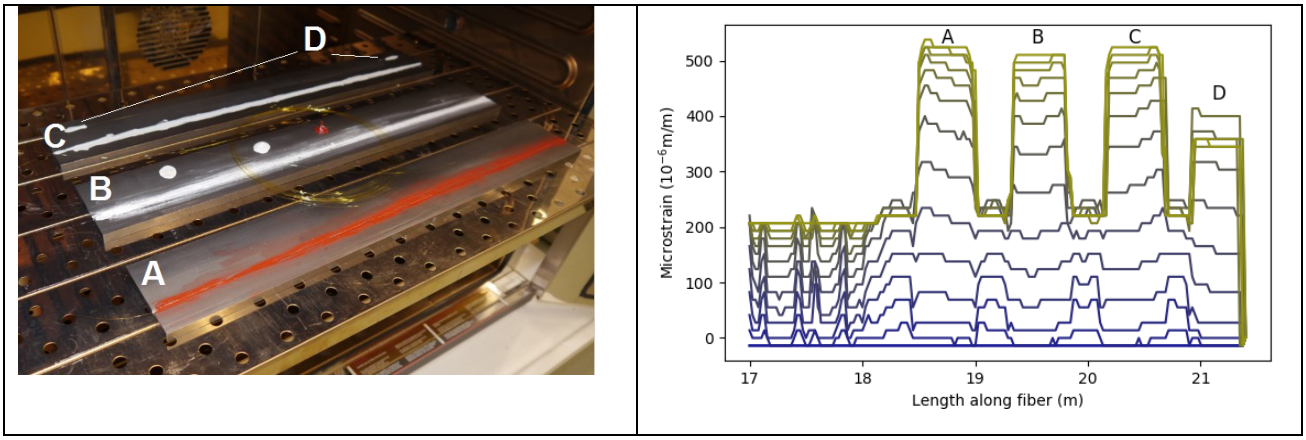


Figure 4: Laboratory setup to test different glue types (left) and raw test results from distributed strain sensing (right) during heating

5. CONCLUSION

The objective of the GeConnect project was described. Loads from constrained thermal expansion, that occur in the production casing of a geothermal well, is simulated by cementing in a typical casing size of 9⅝″ into a 13⅜″ casing and feeding hot steam through the test setup. The function of flexible coupling that is included in the inner casing will be tested at real geothermal conditions. Additionally, one outcomes of the test are to analyze when and at what temperature a micro-annulus will form, i.e. the debonding of the casing-cement interface. This information is then used to predict the performance of the flexible casing on field scale and to determine a potential transition bonding zone over the length of the casing segment.

6. ACKNOWLEDGEMENT

The GeConnect project (Geothermal Casing Connections for Axial Stress Mitigation), coordinated by ÍSOR, is funded through the ERANET cofund GEOTHERMICA (Project no. 731117), from the European Commission, Technology Development Fund (Iceland), Bundesministerium für Wirtschaft und Energie aufgrund eines Beschlusses des Deutschen Bundestages (Germany) and Ministerie van Economische Zaken (The Netherlands).

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