INTEGRITY MONITORING OF GEOTHERMAL WELLS USING FIBER OPTIC DISTRIBUTED STRAIN SENSING TECHNIQUES

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ABSTRACT

High temperature and pressure changes which are encountered in geothermal wells are challenging for an intact well integrity. During operation of such wells, downhole information about the status of casing and cement is limited and usually requires to shut-in the well. We focus on the application of fiber optic distributed sensors for real-time well integrity monitoring. Installing a fiber optic cable permanently in the annulus between casing and cement allows permanent monitoring of parameters such as temperature, strain and noise along the entire length of the cable. This work shows fiber optic field data from the well completion of a low-enthalpy well for geothermal energy storage (Gt BChb1/2015, ATES Fasanenstrasse, Berlin, Germany). In the latter case, gravel and cement pumping was monitored with distributed strain sensing. The pumping of gravel leads to a density change in the annulus which results in a measureable strain reading on the fiber optic cable. A simultaneous measurement with a gamma-gamma density log shows that the strain data from the fiber indicates the position of the gravel head in the annulus. In addition, a delayed consolidation of the gravel packing was monitored with the fiber. During cement pumping, it was observed that fluid shear stresses generate a measureable strain on the cable. The magnitude of these forces can be used to estimate rheological parameters such as fluid density and viscosity of the pumped medium. An experimental study was conducted to validate the field observations. Using distributed strain sensing, we can extract relevant downhole information (such as fluid/material changes) in real-time without interfering with the operational schedule of a well.

1. INTRODUCTION

The structural integrity of casing and cement is of great importance in order to increase the lifetime of a geothermal well and to allow for safe operation. The well has to withstand large temperature and pressure changes during production/injection phases as well as shut-in periods. A proper initial well completion in terms of the cementing operation is the basis for a healthy well. However, hardly any measurement data is available from the subsurface during this construction phase. To study the performance of fluid (and solid) displacement processes in the borehole during cement pumping, this work focuses on real-time well monitoring technologies using fiber optic cables which are permanently installed in the cemented annular space behind the casing.

Distributed fiber optic sensing techniques were developed and tested to simultaneously measure temperature and strain both in bare fibers as well as complex multilayer optical cables. The technologies include distributed temperature sensing (DTS), based on Raman scattering, as well as distributed strain sensing (DSS) which is based on Rayleigh scattering. Acquired DSS data from a well installation during a sand control gravel packing operation was compared to conventional wireline-logging data.

2. DISTRIBUTED FIBER-OPTIC SENSING

When light from an appropriate laser is coupled into an optical fiber, the photons are guided within the core of the fiber. As the light travels along the fiber, a small portion of the photons are scattered due to random but on average uniformly distributed impurities. Generally, distributed fiber optic interrogators detect the backscattered light. Scattering occurs due to three different processes which are the elastic Rayleigh scattering and the inelastic Raman- and Brillouin scattering. The measurement of these photos can be used to measure temperature and strain. The physical origin of the backscattered signal can be obtained from the two-way travel time of the light inside the fiber. Given the speed of light in the vacuum c and the refractive index of the fiber n, the physical location can be obtained:

$$l = \frac{t \cdot c}{2 \cdot n} \tag{1}$$

2.1 Distributed temperature sensing

The term distributed temperature sensing (DTS) typically refers to the technology to measure quasi-continuous temperature profiles along an optical fiber with a high temporal and spatial resolution. The physical principle typically relies on the inelastic Raman scattering phenomenon and is described in Hartog (1983). A laser pulse is coupled into an optical fiber and the backscattered light is analyzed in the Stokes and Anti-Stokes frequency band. The two way travel time of the laser pulse is indicative of the physical location of the scattering process (optical time domain reflectometry, OTDR) and the backscattered intensity is sensitive to the ambient temperature. Hence, the scattering process can be used for distributed temperature sensing.

In addition to DTS systems based on Raman scattering from a pulsed laser (OTDR), other implementations are available. Within this study, however, an OTDR implementation based on Raman scattering is used for temperature measurement.

2.2 Distributed strain sensing

DSS describes the technology to use each location of a fiber as a sensor for deformation. Various different measuring principles are available on the market. Masoudi and Newson (2016) provide a broad overview of distributed strain measurement technologies along optical fibers. The length change Δl of a fiber relative to its initial length L_0 is commonly expressed as strain ε:

$$\varepsilon = \frac{\Delta l}{L_0} \qquad (2)$$

Standard silica fibers are usually proof tested to withstand elongations of 1%, or 10000 με. The detection of strain is possible due to a number of intrinsic properties of the fiber. The most prominent technology for DSS is based on Brillouin Optical Frequency Domain Analysis BOFDA (Garus et al., 1997). Commercially available BOFDA systems provide a strain accuracy of 2 με at a spatial resolution of 1 m up to 50 km. This technology requires access from both end of the fiber. For single ended fiber optic strain measurements, measurement principles are available.

Fiber bragg gratings (FBG) are periodic, artificial changes of the refractive index of the fiber. The effective refractive index n_{eff} is defined by the ratio of the fiber core and the artificially induced gratings. A narrow band of the incident optical light within the fiber is reflected by successive, coherent scattering from the index variation. The strongest interaction occurs at the Bragg wavelength λ_B according to:

$$\lambda_B = 2n_{eff}\Lambda \qquad (3)$$

where Λ is the grating period. A schematic illustration of the FBG principle is shown in figure 1. Strain sensitivity from λ_B origins from the change in Λ due to deformation and from a change in n_{eff} due to the strain optic effect (Bertholds and Dandliker, 1988). A wavelength change from λ_B can also occur with temperature variations. Temperature sensitivity from λ_B origins from thermal expansion of the fiber and hence a change in Λ, and a change of n_{eff} from the thermo optic effect. (Adamovski et al. , 2012).

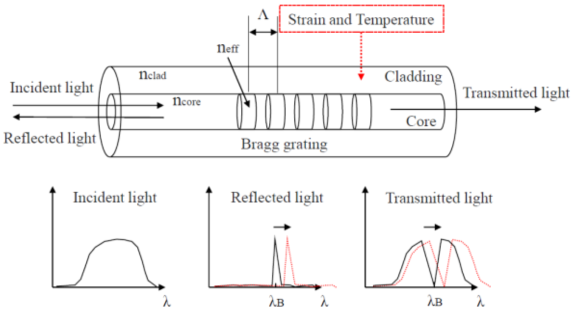

Figure 1: Sketch of a fiber-bragg-grating (FBG) as an analogy for OFDR functioning.

This wavelength-strain dependent property of fibers does not necessarily requires FGB writings. Natural heterogeneity of molecules that make up the fiber can be used as weak, randomly distributed FBG with arbitrary grating period. Although being random, the signal is steady and repeatable. Therefore, every fiber has its own unique spectral fingerprint at a given thermal and mechanical state. Changing the temperature or the stress state at any interval of a fiber will lead to a linear shift in the spectral response Δν of the backscattered light of that fiber interval. A change in Δν due to a change in temperature and/or strain is given by the equation:

$$\Delta \upsilon = \frac{\Delta T}{K_T} + \frac{\Delta \varepsilon}{K_\varepsilon} \qquad (4)$$

where K_T and K_ε are temperature and strain calibration constants: K_T = -0.801 °C/GHz and K_ε = -6.67 με/GHz (Froggatt and Moore, 1998). Those constants are valid for most fiber cores which are doped with germanium. In this study, an OFDR system is used for strain sensing.

LABORATORY EXPERIMENTS

Laboratory experiments were performed using an OBR4400 interrogator as a distributed strain sensing system for wellbore monitoring. The first experimental set-up is used to calibrate temperature and strain sensitivity on a bare fiber (see figure 2). The experiment consists of an optical fiber which is firmly wrapped around cylinders of materials with different thermal expansion coefficients. During heating, parts of the fiber are only exposed to temperature changes, while other experience both temperature and strain changes. Both parameters show a high linearity for the tested range of ΔT=67°C and Δε =3300 με. A second experimental set-up is used to calibrate the strain transfer in a multilayer cable (see figure 3). A cable sample is mounted vertically in the laboratory. In a distance of 1m below a cable clamp, weight pieces are mounted to the cable and the strain response is measured over time. In this cable example, the fibers are embedded in a gel, surrounded by a metal tube, bronze wires and a PE outer sheath. The left subplot shows the strain response of the cable after placement of a 100 g weight piece just after the weight was placed, after 5 minutes and after 10 minutes. The gel filling between the fibers and the various different layers/compounds of the cable result in a complex mechanical interaction across the cable layers. Due to the deformation of gel, the strain on the fiber reduces with time after a weight placement. The experiment shows a hysteresis effect after removing a mechanical load from the cable. The DSS trace also shows that the strain response exceeds the mechanical clamping locations of the free hanging cable. The right subplot shows strain data for different weight pieces during increasing weights and during decreasing weights. In addition, an analytical approach was used to model the strain response of the rigid cable.

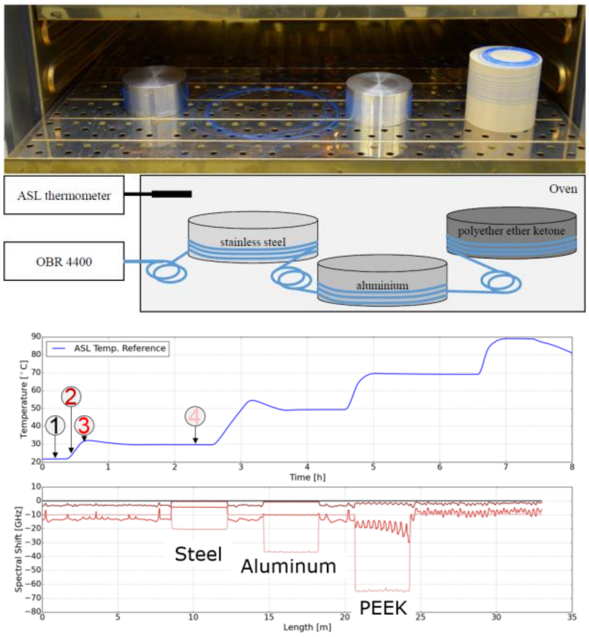

Figure 2: Experimental setup with wrapped optical fiber around cylinders with different thermal expansion coefficient.

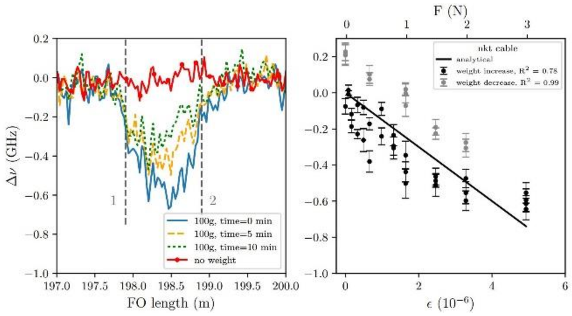

Figure 3: Strain response of a complex multilayer cable. Left subplot: Example of a DSS profile during mechanical perturbation with a mass piece of 100 g for different times after weight placement. Right subplot: analytical and experimental result of the correlation of strain over spectral shift (Lipus et al., 2018).

FIELD INSTALLATION

This work shows field data from a low-enthalpy well for geothermal energy storage (Gt BChb1/2015, ATES Fasanenstrasse, Berlin, Germany). A gravel packing operation and cement pumping was monitored with DTS and DSS (Lipus et al., 2018). The gravel packing has no effect on DTS data, but it shows in the DSS data (see figure 4). During the gravel packing, a conventional wireline γγ-density-log was run to measure the setting height of the gravel in the annulus (depicted with black crosses). At the location where the optical cable was overlaid by gravel, the fiber experiences a relative compression/relaxation of up to 4 $\mu\epsilon$. At locations where the cable is clamped to the casing, the strain effect reduces. After the end of the wireline logging campaign, the downhole fiber experienced an abrupt change towards cable extension. This gives indication that the gravel head kept compaction even after the placement has ended.

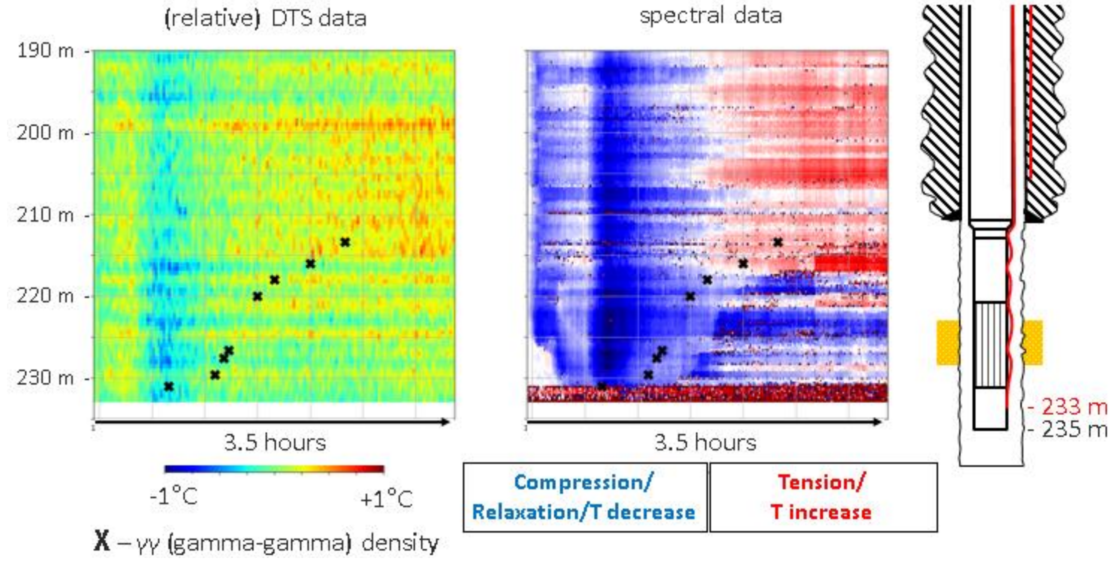

Figure 4: Field data from a shallow ATES well during gravel packing (Gt BChb1/2015, ATES Fasanenstrasse, Berlin, Germany). Downhole relative DTS and DSS data shown over a time of 3.5 hours.

3. CONCLUSIONS

This work shows practical applications of DSS technology during the completion phase of geothermal wells. DSS data shows a relaxation of the cable when fluids are displaced by gravel in the annular space. DSS data matches conventional wireline γγ-density-logging data. It is shown that even a cable with non-optimized design for strain sensing can be utilized to acquire DSS data. Based on the learnings from the laboratory and field experiments, the installation of an optical fiber based strain sensing system is planned in the framework of the GeConnect project (www.geothermalresearch.eu/geconnect). Here, an optical fiber will be used to measure deformation during testing of a full scale prototype of an innovative flexible coupling in real working environment.

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