Applications of Distributed Fiber Optic Strain Sensing for Real-Time Wellbore Integrity Monitoring

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ABSTRACT

The integrity of casing and cement is of utmost importance in order to increase the lifecycle and to improve safe operations of geothermal wells. This contribution focuses on the potential of real-time downhole monitoring techniques along fiber optic cables which are permanently installed behind casing. Distributed fiber optic temperature and strain sensing technology are used to measure thermal as well as load signatures during the completion of a low-enthalpy well for geothermal energy storage (Gt BChb1/2015, ATES Fasanenstrasse, Berlin, Germany). 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

Casing and cement integrity is essential to assure safe operations over the lifecycle of geothermal wells. Especially in the context of high enthalpy geothermal wells, the well architecture has to withstand large temperature and pressure variations during production/injection phases and shut-in periods. Proper cementing operations are fundamental to assure quality sealing areas among open hole and casing annular spaces and assure well integrity policies. However, downhole flow mechanics data measured in real time is not available while the cement slurry is being pumped down. Regular acquired data from the cementing process is usually restricted to flow rates and pressure readings at the cementing and line pumps on surface. Once the cement pumping is finished, cement evaluation downhole logging tools are run into the well to assess the quality and distribution of the cement around the casing.

To analyse the downhole performance of mud displacement and cement slurry during the cementing processes, this work focuses on real-time well monitoring technologies using fiber optic cables which are installed in the annular space behind casing. The technologies comprise distributed temperature sensing (DTS) based on Raman scattering and distributed strain sensing (DSS) based on Rayleigh scattering. Field data was acquired from a shallow well for aquifer thermal energy storage (ATES). Results from DSS and DTS technology are shown for the well completion during a sand control gravel packing operation and compared to conventional gamma-gamma-density wireline-logging data. In addition, DTS and DSS data are shown during the cement pumping.

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 fraction 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 photons can be used to determine temperature and strain along the fiber. The physical origin of the backscattered signal can be obtained from the two-way travel time of the light inside the fiber (optical time domain reflectometry, OTDR):

\[ l = \frac{t \cdot c}{2 \cdot n} \]  

where \( t \) is the 2-way traveling time of the light through the fiber, \( c \) is the speed of light in the vacuum and \( n \) the index of refraction of the glass fiber.

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. While the intensity of the Stokes band is nearly unaffected by temperature variations, the intensity of the Anti-Stokes band changes strongly depending on the temperature. By calculating the ratio of the two peaks, a direct translation to absolute temperature values is possible given the fact that the optical cable was calibrated in the laboratory beforehand.
2.2 Distributed strain sensing

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 $\Delta l$ of a fiber relative to its initial length $L_0$ is commonly expressed as strain $\varepsilon$:

$$\varepsilon = \frac{\Delta l}{L_0}$$

(2)

In this work, we use an Optical Backscatter Reflectometer (OBR 4400 by LUNA Technologies) which is based on Optical Frequency Domain Reflectometry (OFDR). The physical background of this technique has been described in detail in previous publications (e.g. Moore 2011 and Liehr 2015). In a nutshell, an OBR measurement trace can be regarded as a spectral fingerprint of the measurement fiber at a given temperature and strain condition. Changing the temperature or applying strain at any interval of a fiber will lead to a linear shift in the spectral response $\Delta \nu$ of the backscattered light of that fiber interval. The measurement of a reference trace is required as a base line. Any subsequent strain and temperature changes will be measured with respect to that reference trace. Strain sensitivity from $\Delta \nu$ originates from the deformation and hence rearrangement of the molecules in the glass and from a change in the refractive index due to the strain optic effect (Bertholds and Dandliker, 1988). A wavelength change from $\Delta \nu$ can also occur with temperature variations. Temperature sensitivity from $\Delta \nu$ originates from thermal expansion of the fiber and hence a change in the arrangement of the molecules, and a change of the refractive index from the thermo optic effect. (Adamovski et al., 2012). A change in the spectral response $\Delta \nu$ due to a change in temperature and/or strain is given by the equation:

$$\Delta \nu = \frac{\Delta T}{K_T} + \frac{\Delta \varepsilon}{K_\varepsilon}$$

(4)

where $K_T$ and $K_\varepsilon$ are temperature and strain calibration constants: $K_T = -0.801{^\circ}\text{C}/\text{GHz}$ and $K_\varepsilon = -6.67\mu\text{e}/\text{GHz}$ (Froggatt and Moore, 1998). Those constants are valid for most fiber cores which are doped with germanium. A decrease in temperature, reduction in strain (compression or relaxation) lead to positive spectral shifts. An increase in temperature and increase in strain create negative spectral shifts.

3. LABORATORY EXPERIMENTS

In order to analyse strain and temperature results acquired in the field, laboratory experiments were performed to access the potential of using the 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 1). 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. The additional strain experience by the fiber matches the expected thermal expansion from the different material cylinders. Subsequently, a second experimental set-up was used to calibrate the strain transfer in different multilayer cable (see figure 2). Strain responses from tight-buffer and fiber-in-loose-tube (FIMT) cables were characterized and compared. For the tested gel filled FIMT cable, the gel deformation could be observed over time (Lipus et al., 2018).

Figure 1: Experimental setup with wrapped optical fiber around cylinders with different thermal expansion coefficient.
4. FIELD DATA

This section focuses on fiber optic field data from an exploration well for aquifer thermal energy storage (ATES) in Berlin, Germany (Gt BChb1/2015). Figure 3 shows DTS data which was monitored in the annulus during the gravel pack installation and cement pumping down in the well. In addition to DTS monitoring, DSS data was also acquired during the gravel packing operation and cement pumping (Lipus et al. 2018). We did not observe any downhole temperature changes from DTS as a consequence of the gravel pack installation. However, the DSS data shows a strain effect in form of an apparent compression/relaxation of the fiber optic cable (see figure 4). This strain signal is confined to the depth interval in which the gravel was monitored. The DSS data also shows that the cable clamping locations reduce relative strain changes along the cable. At the end of the wireline logging campaign executed to detect the gravel setting height, it was observed that the downhole fiber experienced an abrupt change towards cable extension (last trace in Phase 3). A second logging of the gravel head setting height during the next working day revealed a lowering of the gravel head by a couple of meters. The strain measured by the cable suggests a sudden drop of the gravel head in the annulus.

Figure 5 shows the DTS data relative to the temperature state before start pumping cement slurry and the temperature corrected DSS data over the same time window (close up of the cement pumping window in figure 3). In terms of temperature, the cement suspension showed as a relative warm temperature perturbation which moved upwards in the annulus in time. Changes in cement pumping rates are depicted by different gradients of height over time. The DSS plot additionally shows a tensional fringe at the interface in between the cement slurry and the foregoing spacer fluid. This mechanical attribute is only confined to the interface between spacer and cement head and quickly fades as the cement head rises in the annulus.

Figure 2: DSS testing of a stiff cable (cable type 1) and a cable specifically designed to pick up strain (cable type 2) (Lipus et al. 2018)

Figure 3: DTS measurement campaign during gravel packing and cementation of Gt BChb1/2015 (Reinsch et al. 2019)
Lipus et al.

Figure 4: Field data from a shallow ATES well during gravel packing (Gt BChb1/2015). Wireline $\gamma\gamma$-density and DSS data shown over a time. Black bars on left subplot show cable clamping locations. Green arrow indicates gravel head (Lipus et al. 2018)

Figure 5: Relative DTS data and DSS (spectral) data during cement pumping in Gt BChb1/2015

5. CONCLUSIONS

This work shows practical applications of fiber optic technology during the completion and operation 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 gamma-gamma-density-logging data. It is shown that even a cable with non-optimized design for strain sensing can be utilized to acquire DSS data. During cement pumping, a tensional signal was measured close to the interface between fluid spacer and lead cement slurry. This observation gives indications that DSS data can be applied to study fluid rheological parameters. On the basis of this observations, laboratory experiments are currently being conducted to investigate the potential of measuring downhole rheological parameters using DSS technologies. In addition, 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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