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Field Evaluation of Dual-Ended, High Temperature, Hydrogen Tolerant Fiber Optic DTS Sensor With Compact Fiber Loop Assembly

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Abstract

Fiber-optic sensors have experienced meaningful adoption by the Oil & Gas industry, with the unique ability to be configured in fully distributed sensing architectures, capable of real-time monitoring of an entire well-bore cost-effectively over conventional sensors. Raman type optical distributed temperature sensors (DTS) are most prevalent in being the simplest to implement, yet are especially prone to adverse effects of the well environment, particularly hydrogen present in the well that can significantly degrade measurement performance and reliability. While these effects can be mitigated through use of hermetic hydrogen-blocking cables and other measures, they become even more acute at higher temperature, and the problem compounded by the lack of such hermetic solutions at temperatures common to thermal recovery operations, leading to measurement error and poor reliability. This paper reports field results of a high temperature, hydrogen-tolerant DTS system that incorporates novel hydrogen tolerant dual-fiber downhole sensing cable packaged with a novel compact guided-wave fiber turnaround device. The dual-fiber architecture allows a dual-ended measurement protocol and use of a novel differential fiber attenuation compensation algorithm. Field results of the DTS system both permanently installed and run-in surveys in operating SAGD wells are compared to downhole thermocouple sensor references. Field performance rivals that of the best optical sensors demonstrated in this application, while providing high spatial resolution and full wellbore coverage inherent with Raman systems. Aging effects and analysis after 2,500 hours- well past the point where typical DTS sensors fail, support sensor rating for continuous operation at 300°C for several years.

Introduction

The most prevalent fiber optic sensor products today are Raman-type distributed temperature sensors (DTS) in which an optical fiber is probed with a pulsed laser to stimulate temperature-encoded Raman backscattered light that is detected and analyzed to record a temperature measurement every meter or so along the sensing fiber using optical time-delay reflectometry (OTDR) methods. Raman-type DTS is the most common fiber optic sensor used in upstream Oil & Gas by virtue of being the most mature and ready to implement, and is attractive for providing unique full well-bore thermal profiling in real time. In any downhole application, adverse effects of hydrogen on DTS performance and reliability must be addressed, which is usually accomplished through use of hermetic hydrogen-blocking cables and other measures to prevent hydrogen diffusion into the sensing fiber. Hydrogen effects become even more acute at higher temperature, and the problem compounded by the lack of hermetic solutions at temperatures associated with most thermal recovery operations, leading to frequent failures and poor reliability for fiber optics serving this sector.

Without the ability to prevent hydrogen diffusion into downhole sensing cables, hydrogen-induced attenuation- so called “fiber darkening” is the principal source of failure for fiber optics in SAGD applications. Catastrophic loss of signal has been the primary failure mode of these systems, however degradation of measurement accuracy and performance precedes this event. Fiber optics applied in this sector hence must be designed under the premise of operating under full exposure to hydrogen, in the context of reliability and measurement performance. More recent solutions for operating fiber optic sensors in this environment are based on refinement of high temperature, hydrogen-tolerant optical sensing fibers, and novel dual-ended downhole sensor architecture and measurement protocols that allow compensation of hydrogen-induced measurement errors.

These solutions are captured in a DTS system designed specifically for SAGD application and introduced in 2010 to this sector. Field results of the system permanently installed in an operating SAGD well and in retrievable surveys are reported in this paper, and support the suitability of the system in these wells. This paper will first review hydrogen effects and mitigation specific to sensing fiber optical reliability, and hydrogen effects on measurement performance of which Raman DTS systems are especially prone. A discussion will then review the reported DTS system key component and design features. The paper will conclude with preliminary field results that validate the design and use of these sensors in the intended SAGD environment, demonstrating reliability and good correlation to downhole thermal references.

Hydrogen Effects

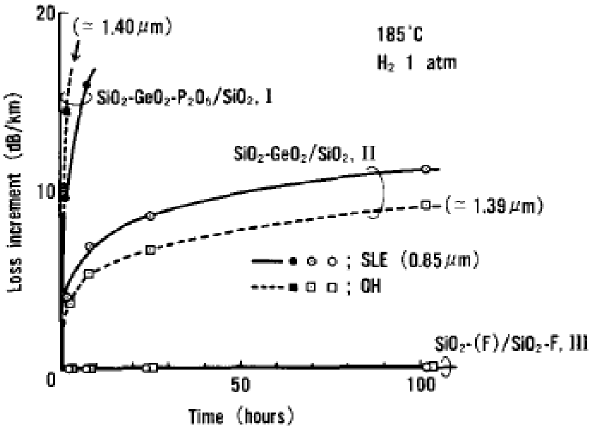
Based on quartz optical fibers, fiber optic sensors have long been viewed as an upgrade technology for high temperature logging applications. Conventional tools such as thermo-couples, while proven at elevated temperatures, are not practical for installing a desired number of sensors to give a full spatial representation across the entire well-bore. Fiber optic sensors, in particular DTS, become especially attractive in providing full wellbore profiling. In recent years however, the hydrogen problem has reemerged with extensions of conventional oil and gas fiber optic sensing cables, rated upwards to 180°C, when deployed in higher temperature thermal recovery wells, where they have experienced significant hydrogen-induced failure. While these steel armored cables survive mechanically in this environment through use of high temperature polymer fiber coatings, they are prone to hydrogen diffusion as hermetic materials compatible with oil and gas optical sensing cables are ineffective at temperatures above 200°C.

Hydrogen is ubiquitous in any well environment due to formation chemistry, and the liberation of hydrogen the product of galvanic reaction between well fluids and steel completion parts. Hydrogen diffusion in optical fiber can manifest into both transient and permanent attenuation in which the magnitude of latter in conventional fibers, is dominant and highly dependent on the glass composition of the optical fiber itself. Transient losses are reversible, caused by absorption due to dissolved hydrogen in the glass. Once hydrogen is removed, the fiber returns to its original clarity. In contrast, permanent losses are irreversible, caused by chemical reactions of hydrogen with glass precursor defects that form light absorbing species with strong absorption in the near-infrared band where most fiber optic systems operate.

Hydrogen loss growth is dependent first on hydrogen diffusion rate, a function of temperature, in which initial transient loss is observed, its magnitude governed by the hydrogen solubility in the glass, which quickly achieves equilibrium as a function of temperature and hydrogen partial pressure. Transient loss is uniform across different fiber types, as the solubility of hydrogen in the glass is independent of fiber type, and achieves equilibrium once hydrogen diffusion reaches saturation. From there, in conventional fibers, growth in permanent losses begins to take over, in which loss growth is relatively complex and difficult to predict. Chemical reactions that drive permanent losses are more complex, a function of defect type, their concentration, and the activation energy of bonding and valence specific to each reaction. The type of defect and population is dependent upon the glass composition, and subtleties of the fiber manufacturing process.

Hydrogen Tolerant Pure Silica Core Fiber

The magnitude of permanent hydrogen loss has been found to be directly dependent upon the amount of refractive-index modifying glass dopants such as Ge- and P- oxides used in conventional telecom fibers. This can be seen in figure below[1] that shows growth in attenuation for example fibers with different dopant profiles exposed to pure hydrogen at 185°C and 1atm hydrogen partial pressure. Of the three types, pure silica core with fluorinated cladding show superior response with no discernable loss increase-representative performance for this class of fibers. This is a result of the absence of dopants in the core that practically eliminates all precursor defects, with only Si diamagnetic centers contributing to hydroxyl formation, with absorption at 1385nm, the primary permanent loss effect common in these fibers. Furthermore, fluorinated cladding materials have been shown to not adversely affect hydrogen performance of these fibers.



Such pure silica core fibers are uniformly resistant to hydrogen aging and induced attenuation effects, to operate effectively in high temperature hydrogen environments in which permanent losses, if any, are minimal. While these fibers are still subject to transient hydrogen ingress, the associated loss likewise is minimal and manageable due to the low hydrogen solubility at typical temperature and hydrogen partial pressure regimes seen in downhole SAGD wells.

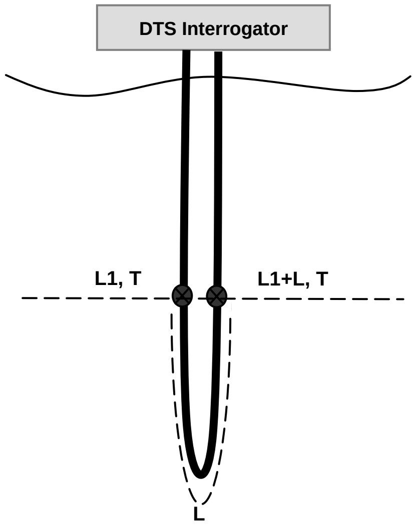
Hydrogen Compensation of DTS Measurements

Hydrogen diffusion and associated light attenuation, even when minimized through use of pure silica core fiber, is especially problematic with intensity-modulated Raman DTS sensors, leading to measurement error. These sensors exploit Raman scatter effects of high intensity light launched into a sensing fiber, in which in the interaction between the propagating light pulse and the glass material, part of the light energy is transferred, and subsequent loss of energy increases the wavelength of light (Stokes-shift), while the transferred energy can be donated to excited state atoms to cause decreased wavelength (Anti-Stokes shift). The amount of energy donated, and relative intensity of Anti-Stokes shifted light, is related to the amount of atoms in an excited state, a function of temperature. In practical DTS systems, light pulses are launched into a sensing fiber and the return time and intensity of Raman backscattered signals recorded to calculate temperature at specific locations all along the fiber to yield a fully distributed temperature sensor.

These systems detect slight change in the ratio of Stokes/Anti-Stokes intensity to calculate temperature, in which typical scale factor is a mere 0.01dB/°C for near-infrared laser excited systems. Prior to installation, the sensing fiber or cable must be calibrated for each individual sensing fiber as the intrinsic optical attenuation rate at these wavelengths, and other intrinsic parameters that affect the temperature measurement, will vary among different sensing fibers, and must be precisely characterized each individual sensing fiber for DTS measurement accuracy. Once installed, successful operation of these sensors for high quality of data requires maintaining the calibrated fiber under conditions that preserve these calibration parameters. However DTS calibration is quickly offset by external influences that promote differential fiber attenuation (DFA) between the Stokes/Anti-Stokes lines that will degrade measurement accuracy. Such DFA, in which transient hydrogen-induced attenuation is a main source in SAGD wells, is not readily distinguishable from thermally-induced modulation of the Stokes/Anti-Stokes intensities. The magnitude of the subsequent error can be quite significant-tens even hundreds of degrees celcius, even for small amounts of transient hydrogen loss due to the small Stokes/Anti-stokes intensity scale factor.

To mitigate this measurement error in high temperature DTS systems that operate under direct hydrogen exposure, dual-fiber/dual-ended sensing configurations and measurement protocols are used to characterize DFA along the sensing fiber to allow mathematical correction of the calculated temperature. The most common architecture to implement this protocol is where the sensing cable is looped or returned from bottom, to provide access and sensor interrogation to both ends at surface. Referring to the figure, a simplified model has two positions of the cable at common depth, separated by a distance L, and are assumed be at identical temperature. If the cable length between the two sensing points experiences a differential loss, there will be a temperature difference between the two points. This temperature difference is then used to compensate the particular length of fiber between the two points and correct for the temperature difference.

While such dual-ended DTS measurement protocols and compensation methods have proven effective, their implementation has been difficult due to the confined space to install and accommodate mechanical movement of fiber splice connection or other sensor/cable hardware within the well completion. Typical distal fiber splice enclosures, pumped-fiber loops and other turnaround hardware used to create dual-ended architectures in SAGD wells, for the most part have a larger, more obstructive profile than the sensing cable. These features tend to interact mechanically with other completion parts, especially during thermal cycling, and are a frequent point of mechanical failure and overall a primary reliability risk of the downhole DTS system.



High Temperature DTS System

The reported DTS system overcomes this shortcoming through use of a novel, compact guided wave optical turnaround device, with the system also incorporating key solutions previously discussed to yield a system designed and qualified to operate under continuous, long-term direct hydrogen exposure with high reliability and measurement performance. Unlike most fiber optic systems deployed in SAGD wells, this system was designed specifically for this application and environments. Major system components and features of this system are described in the following.

High Reliability, Hydrogen-Tolerant Optical Sensing Cable

At the core of the downhole sensing system is the optical sensing cable that maintains the sensing fiber in a low strain condition over thermal cycling and endures the mechanical rigors of handling during installation and subsequent well operations. The sensing fiber has been extensively tested first by the manufacturer and then by QOREX at its hydrogen test facility. The fiber screening and qualification testing for the 300°C rating of this fiber exceeds that of any test program reported or that the authors are aware. The screening and qualification process involved multi-lot thermal aging and mechanical reliability tests based on dynamic tensile fatigueto failure testing to generate Weibull statistics. Hydrogen testing was performed under multiple thermal and hydrogen atmospheric conditions to cover a broad range of conditions to initiate reaction of different precursor defects with varying activation energy.

After screening, the fiber is treated to an additional preconditioning process to impart engineered optical and mechanical properties of the fiber for optimum performance at the cable level. A pair of these fibers is then encased in protective cable of all-metal construction designed to convey, seal and protect the fiber from well fluids and rigors of installation. These cables feature a design excess fiber length within the cable to bias thermal expansion mismatch between the metal cable and glass optical fiber to maintain the fiber in a low strain condition over repeated thermal cycling.

The ¼" alloy armor cable outer form factor is compatible with conventional well installation equipment and procedures. Furthermore the compact turnaround and dual fiber sensor package is uniquely versatile and robust to open up installation options previously not available with other dual-ended systems. Aside from the installation method detailed in the paper for the test trial (affixing the cable to the outside of production tubing along with the ESP cable and various other instrument cables), the reported cables can be clamped to any production, injection or casing tubular. The tensile strength and mechanical protection provided by the alloy armor cable allows for various spool-in and pump down installations. The sleek profile and compact size of the turnaround sub allows for easy integration of the cable inside of coiled tubing with other instrumentation as part of Petrospec's Sensor-Tube™ family.

Compact Guided Wave Turnaround Device

The reported system connects the fiber pair at the distal end to implement a continuous looped, dual-ended sensing cable architecture using a novel compact turnaround device. This component is based on guided-wave optical component design with no moving parts. The device has been fully "shake and bake" qualification tested for reliable 300°C operation. Optical transmission properties are stable over the full operating temperature. The device is integrated with the ¼" armor cable in a 3/8" outer diameter all-welded alloy package 20cm in length. This small form factor enable the

Surface Interrogator and Compensation Algorithm

The installed downhole sensor is completely passive, incorporating fiber, cable, and connection hardware designed for reliable mechanical and stable optical performance in the harsh SAGD environment. At surface, both ends of the fiber loop are accessible and probed using an optical switch. The data acquisition unit includes the DTS interrogator, switch unit, and controller module that commands the system to run through a dual-ended DTS scan and measurement protocol, and then applies a proprietary compensation algorithm. As opposed to other single point or averaged compensation algorithms, the reported system algorithm compensates for all DFA sources in addition to hydrogen, and is more capable of reporting accurate measurements across wells with wide variations in temperature. Of note is the installation flexibility and -55°C to 65°C operating range of the surface interrogator unit, that is suitable for full arctic as well as desert installations without any additional environmental control. Fully functioning, self-contained units packaged in outdoor NEMA4 enclosure are capable of measuring, processing and transmitting wireless data in remote applications. Recently, a solar-powered system was installed in northern Alberta and fully operational at the low temperature extreme.

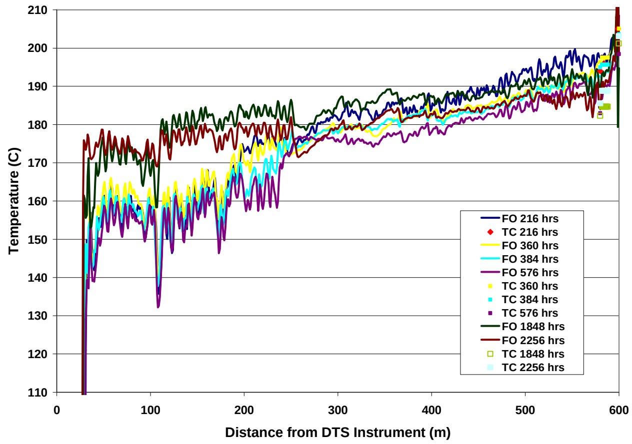
Preliminary Field Results

A field trial cable was assembled and made ready for installation during an electrical submersible pump (ESP) changeout. An operating SAGD well was graciously made available by the operator, and chosen where the DTS cable would not interfere with any well operations, and could be added with slight modification to the tubing clamps. The trial well was determined suitable for a preliminary field validation of the system in offering live SAGD well conditions with temperature in excess of 200°C. This temperature presents an aggressive high temperature hydrogen environment to validate system hydrogen performance and investigate any aging effects, and cycle the cable thermally. In addition, the clamping installation is among the most rigorous installation methods on fiber optic cables that are much less resilient than electrical cables to stretching and crimping typically encountered in these type completions. Further clamp movement and twisting when run in the well can also exacerbate mechanical problems acting on the cable.

The system was installed on November 23, 2010 with the cable landed at 574m. The fiber optic cable was run simultaneously with a ½" OD tube containing 3/16" triplex thermocouples. The tube is also used to purge gas in the annulus for pressure monitoring. Three thermal couples at the motor, intake and pump are located at 574m, 559m, and 555m respectively provide point thermal references. The system was installed using Cannon clamps with inserts machined to accommodate the ¼" fiber optic cable. The clamping system includes one cross-coupling protector and one mid-joint clamp, with additional mid-joint clamps added in the first few joints to increase standoff room for instrumentation. The fiber optic cable was pressure sealed at the wellhead, and exited to a surface spool, cut and pressure sealed. Fibers were connected to a DTS data acquisition module contained in a ruggedized field-portable enclosure.

In the final system commissioning step of installation, the system was operated in OTDR loss measurement mode to check the initial as-installed fiber attenuation, and then switched to acquire temperature data acquisition, with both DTS and collocated thermocouple data collected and stored. This same test sequence was repeated periodically through the last measurement of the reporting period of the preparation of this paper taken on February 25.

Initial installation data for fiber attenuation showed typical loss slope in the first 200m of the cable, with increased attenuation over the next 200m or so. The loss profile indicates a strong possibility of mechanical strain, likely due to the clamping system possibly twisting and pulling on the cable. Despite the excess attenuation, the system has been fully operational, acquiring DTS measurement data with good correlation to reference thermocouples. as shown in the DTS temperature profile below. The DTS plot covers multiple scans taken across the 2,500 hour reporting period. There is a step increase in temperature around 200m that may be attributed to fluid level in the casing, with the thermal structure above possibly due to a more dynamic multi-phase thermal environment.



Although difficult to observe in the data plot, there is good correlation of the DTS data to collocated thermocouples around the ESP. DTS data is within ± 2.0°C agreement or better on average at each location over multiple measurements taken over the report period. The exception was DTS data excursions up to 6°C on a couple scans at the pump thermocouple point at 555m. It should be noted that these excursions were only seen at this location, with other points in good agreement in the same scan, which argues against a measurement problem and more likely subtle difference in sensor mounting and subsequent contact with the thermal environment.

The robustness of the cable is demonstrated in the continued delivery of high quality of data despite apparent mechanical stress of cable clamps and likely twisting and shifting as the completion was landed and heated during installation in the heated production well. It is important to note that cables of the same design are being routinely run in retrievable surveys by Petrospec Engineering in operating SAGD wells that further attests to the ruggedness of the cable. While clamped, production tubing conveyed installations are recognized as the most challenging mechanically on downhole fiber optic cables, retrievable surveys can be considered even more so. The repeated process of mobilization, coiling/uncoiling, and running cables at surface conditions sometimes down to -40°C into hot SAGD wells is extremely arduous on these cables and integrated optical turnaround packaging. Yet despite this difficult handling, these survey cables have shown almost immeasurable change in transmission after numerous surveys and hundreds of operational hours, and continue to deliver a high quality of DTS data with excellent correlation to thermocouple references.

Discussion

Field results in an operating SAGD well are encouraging after over 2,500 hours, a statistically meaningful period of time for preliminary evaluation of these sensors in this application. This timescale is far beyond the period of hydrogen diffusion and reaction with the sensing fiber leading to hydrogen-induced failures that are experienced well within the first few weeks or several hundred hours at typical well conditions. Monitoring both fiber attenuation and correlation of DTS data to thermocouple data periodically over this period also allows for an initial assessment of cable aging and measurement drift. Outside of the suspected mechanical-induced loss upon installation, the mean fiber attenuation change over the 2,500 hour reporting period is 0.15db, normalized to 0.261dB/km. With a power budget in excess of 10dB for this DTS system, this correlates to a lifetime trending over 10 years. While early, there is no observed measurement performance degradation or drift over this initial trial period. These results are promising for the system to deliver high quality of data, within the correlated measurement accuracy of the downhole thermocouple references, over such operating lifetime.

Conclusion

A purpose- designed, engineered, and qualified high temperature DTS system has been introduced for use in SAGD wells. This system features a rugged hydrogen-tolerant fiber optic sensing cable with unique compact fiber turnaround assembly to realize a dual-ended DTS sensor architecture in a small ¼" cable form factor that is amenable to a broader range of installation and applications than previous DTS systems. Initial field results after 2,500 hours are encouraging after being installed in an operating SAGD well, with low observed cable aging and excellent correlation to collocated downhole thermocouple references. Initial lifetime expectation is trending over 10-years, maintaining acquisition and delivery of high quality thermal data.

References

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