FIBER OPTIC SENSING FOR PRODUCTION AND OPERATIONS DIAGNOSTICS: PAST, PRESENT, AND FUTURE

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ABSTRACT

We present a survey of uses for distributed fiber optic sensors (DFOS) in oilfield production and operations. Downhole DFOS measurements of temperature, strain, and noise along the entire length of the wellbore serve as diagnostic tools for flow profiling and artificial lift monitoring. Field cases demonstrate DFOS abilities such as identifying gas lift injection points, evaluating stimulation efficacy, and profiling production and injection volumes.

INTRODUCTION

Distributed fiber optic sensing (DFOS) has been applied for oilfield production and operation diagnostics for at least three decades. In this paper, we seek to provide a survey of uses for DFOS for the benefit of operators seeking novel methods to diagnose production operation issues. In no way is this survey meant to be comprehensive. However, the applications presented here should demonstrate many of the most prominent uses for DFOS in production engineering.

Figure 1 illustrates the basic sensing principle of DFOS. An optical interrogator launches a laser pulse down the length of a fiber optic cable. Random inhomogeneities in the fiber from the manufacturing process act as scattering points or reflectors. These inhomogeneities backscatter a portion of the light pulse back along the fiber towards the optical interrogator. The interrogator measures the backscattered signal, and correlates changes in the backscatter intensity, amplitude, and phase to changes in axial strain and temperature along the fiber. The location of an axial strain or temperature disturbance can be pinpointed based on the two-way travel time of light in the fiber and the known speed of light in the fiber. High sampling frequencies and strain sensitivity enable the detection of strains caused by sound waves. **Figure 2** shows the frequency spectrum of backscattered light and illustrates how different types of sensing correspond to different frequency bands of the backscattered signal. Rayleigh scattering is elastic; the backscattered signal remains at the same frequency as the original light pulse (Hartog 2017). Changes in phase of the backscattered signals are proportional to changes in temperature and strain. Rayleigh phased-based DFOS is typically known as distributed acoustic sensing (DAS). Distributed temperature sensing (DTS) uses the Raman portion of the backscattered signal. Many distributed strain sensing (DSS) interrogators are based on the frequency shift of Brillouin backscatter. Changes in backscattered frequency in this band correspond to changes in temperature and strain.

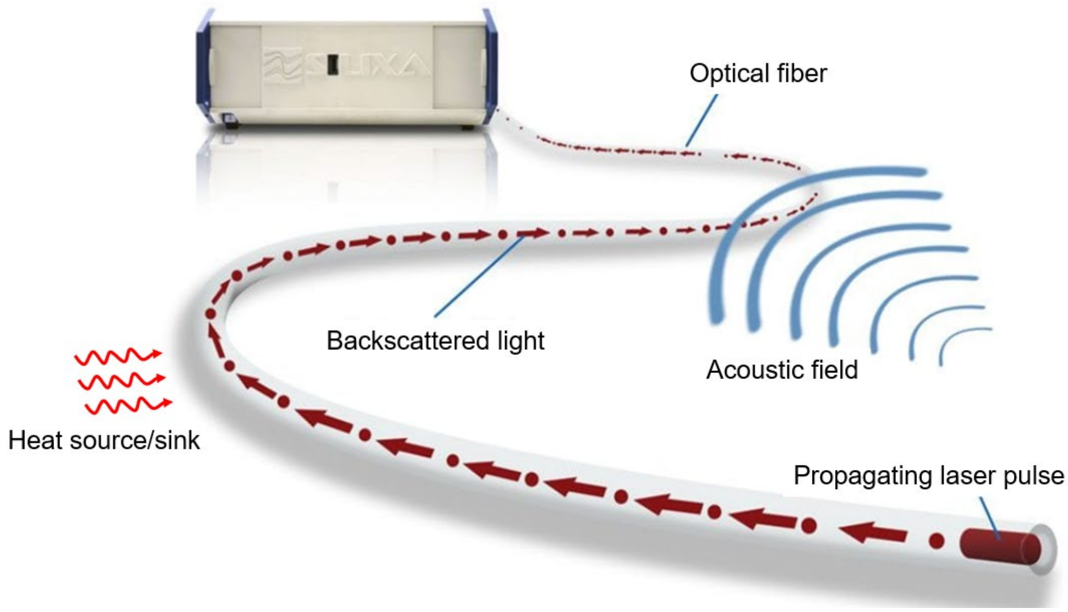

Figure 1 – Illustration of DFOS which uses backscattered light from a laser pulse in fiber optic cables. Adapted from (Silixa, 2021).

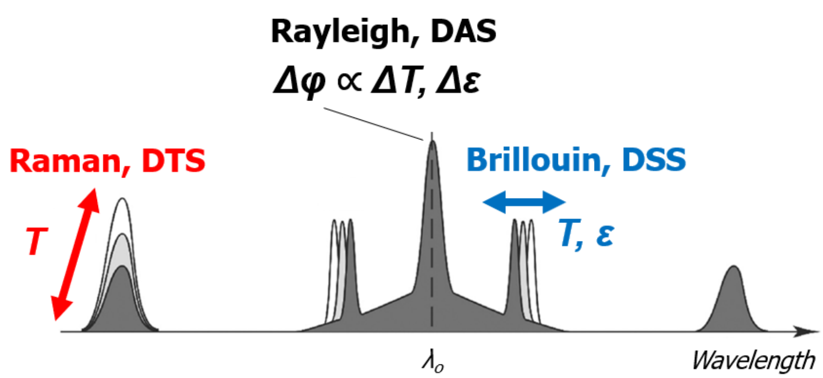

Figure 2 – Different types of backscatter that occur in fiber optic cables and the associated use for distributed sensing.

To install a fiber in a wellbore, the fiber is typically housed in a sealed capillary tubing string or other cables for protection from harsh wellbore environments. There are several different methods to deploy fiber optic cable as shown in **Figure 3**. The fiber can be clamped to and run in with the production casing and cemented in place. This is referred to as a permanent installation. Similarly, the fiber can be clamped to the outside of the production tubing. Temporary deployments of fiber optic cable are also possible. Fiber optic cable can be embedded in slickline, wireline, or a carbon-fiber rod and fed into the wellbore. Additionally, disposable fiber can be deployed by pumping a dart containing a spool of fiber into a well. The fiber unspools as the dart travels down the tubing or casing. This type of fiber is used typically in sealed wellbores to monitor offset completions.

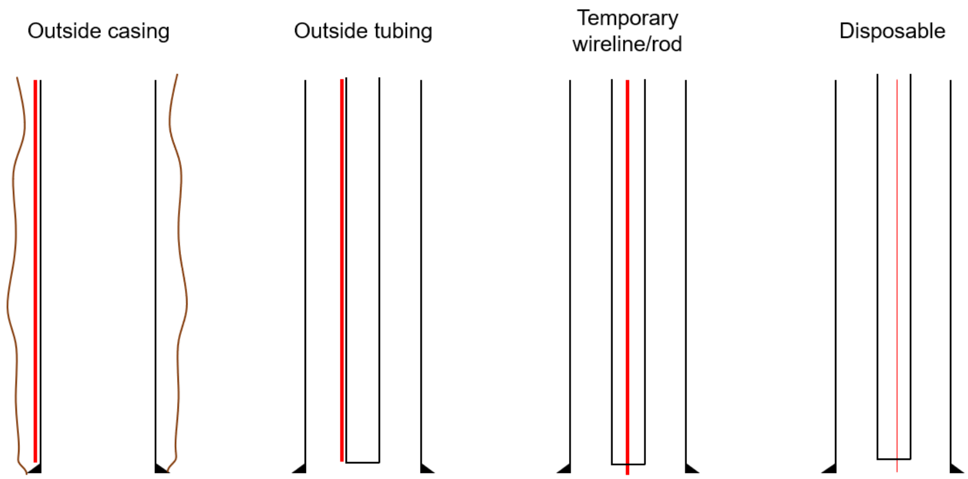

Figure 3 – Different configurations for fiber optic cable placement in a wellbore.

Understanding distributed fiber optic sensors as sensitive to changes in temperature and/or axial strain, and knowledge of the different types of ways to deploy the fiber leads us to a review of applications of DFOS in production and operations. The review is organized roughly chronologically. Distributed temperature sensors were the first DFOSs applied in the oilfield, followed by distributed acoustic and strain sensors. A few paragraphs are devoted to speculation of the future of DFOS in production and operation with potential developments of distributed pressure and chemical sensors.

PAST – EARLY DFOS WITH DISTRIBUTED TEMPERATURE SENSING

Distributed temperature sensing was developed in the 1980’s and was first applied to wellbore temperature measurements in the early 1990’s (Hurtig et al. 1994). DTS remains a commonly used diagnostic tool. By describing DTS measurements as fiber optic technology in the “past,” we simply mean it was the first type of DFOS applied in the oilfield. While many DFOS techniques exhibit dependency on strain and temperature, DTS is unique in that it is insensitive to strain (Hartog 2017). DTS measurements have a resolution of approximately 1 °F for a one-minute acquisition time at wellbore lengths of 10,000 feet. Temperature measurements are reported at approximately one-meter increments along the entire length of the fiber.

Steamflood Monitoring

Perhaps the earliest use of DTS for production monitoring took place in the context of thermal recovery of heavy oil (Saputelli et al. 1999). Early breakthrough in steamflood operations is detrimental to well production. Johnson el al. developed a method to determine which zone or zones experienced steam breakthrough using DTS measurements (Johnson et al. 2002). In their procedure, they:

1. Shut-in the well
2. Pumped cool water down the tubing-casing annulus
3. Obtained a baseline temperature profile of the cooled wellbore using DTS.
4. Opened the well to production
5. Monitored temperature changes.

Figure 4 illustrates temperature profiles before, during, and after pumping the cool water and returning the well to production. After turning the well to production, DTS measurements indicated rapid warmback near Zones 3 and 4. The rapid warmback was attributed to steam breakthrough, enabling remediation to improve production.

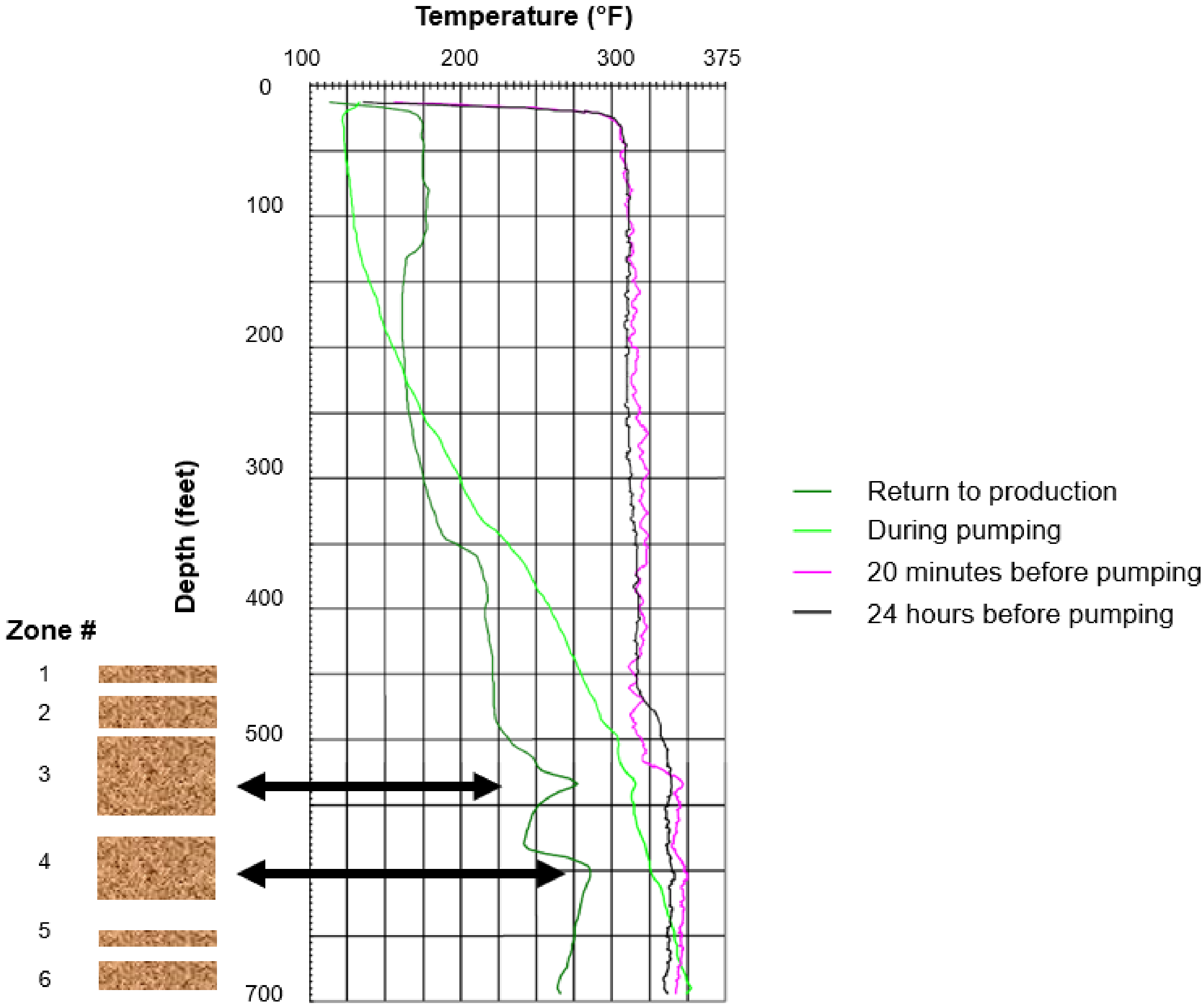

Figure 4 – DTS temperature profiles for diagnosing breakthrough in a steamflood. Adapted from (Johnson et al. 2002).

Gas Production and Gas Lift Surveillance

Joule-Thompson cooling during gas expansion provides a basis for diagnosing gas flow using DTS. **Figure 5** displays simulated temperature profiles during production from multiple gas zones (Huebsch et al. 2008). A logging company deployed DTS in slickline for measurements during gas production. They used a reservoir simulator to invert the DTS temperature measurements for gas production rates. The estimated production rates for each zone agreed within uncertainty to measurements obtained from a traditional production log.

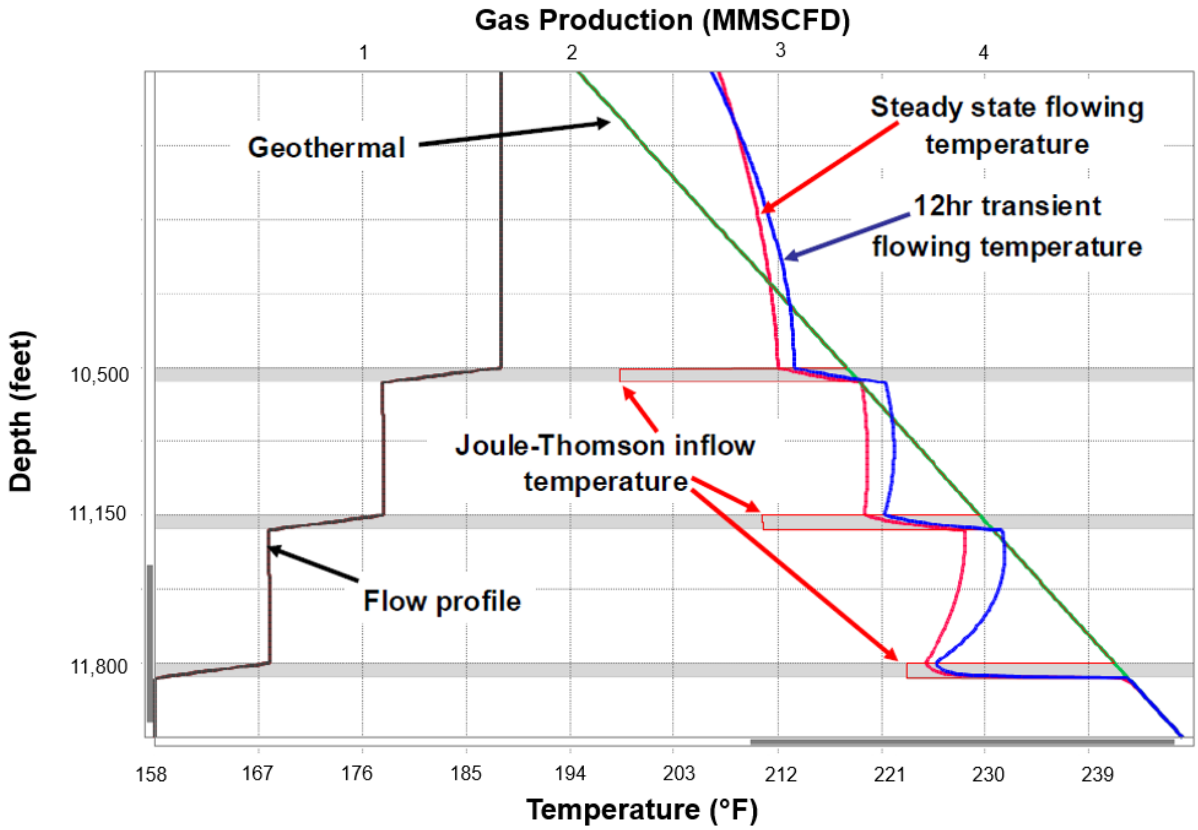

Figure 5 – Simulated temperature measurements during production. The amount of cooling is related to the drawdown and gas production rates from each zone. Adapted from (Huebsch et al. 2008).

The pressure drop experienced by the flow of injected gas through gas lift valves generates measurable cooling. **Figure 6** shows DTS measurements in a gas lifted well from fiber optic cable strapped to the outside of the production tubing (Weaver et al. 2005). Locally cool regions move progressively downward as the well unloads, indicating gas lifting from deeper valves. The third frame exhibits two cool regions, indicating temporary multi-pointing as the lift point transitions. The authors note a delay in the cooling response due to the fiber being located outside the tubing. In some gas lift unloading sequences, cooling was not observed. For DFOS temperature measurements it is preferable, but not always realistic, to have the fiber in close contact with the monitored fluids.

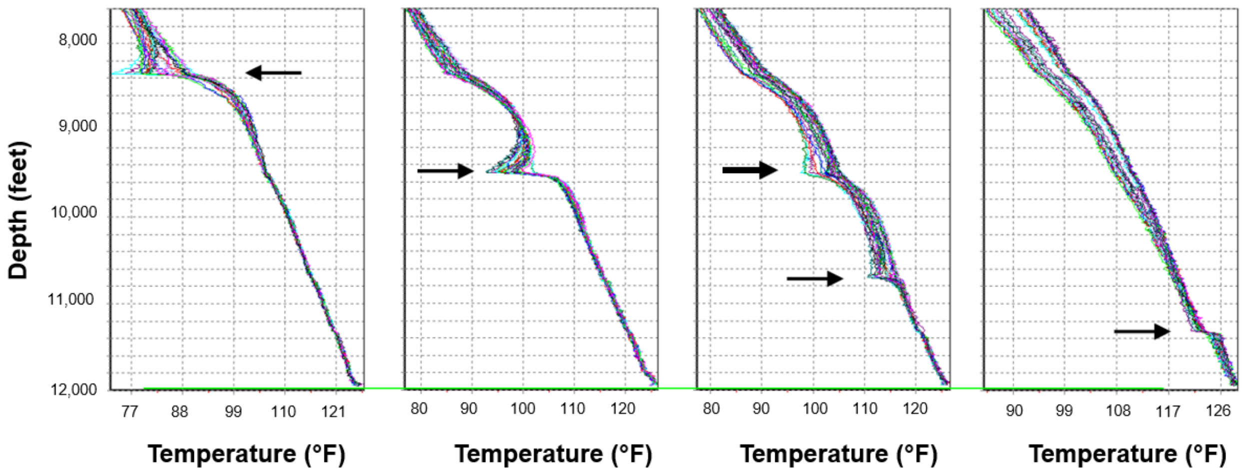

Figure 6 – DTS Temperature profiles indicating Joule-Thompson cooling in a gas lift unloading sequence. Adapted from (Weaver et al. 2005).

Other Uses

Other uses of DTS measurements in production and operations include:

- Pipeline leak detection both on land, subsea, and in arctic environments (Eisler and Lanan 2012, Thodi et al. 2014, Walker and Carr 2003);
- Wax formation monitoring and paraffin treatment optimization (Guzman 2012);
- Diagnosis of injection fluid allocation in acidizing and fracturing treatment in both vertical and horizontal wells (Davis et al. 1997, Glasbergen et al. 2007, Sierra et al. 2008).
- Inflow profiling for gas and multiphase flow in horizontal wells (Zhang and Zhu 2019).

PRESENT – RECENT APPLICATIONS OF DISTRIBUTED ACOUSTIC AND STRAIN SENSING IN PRODUCTION AND OPERATIONS DIAGNOSTICS

Distributed acoustic sensing (DAS) was developed in the early 1990's and debuted in the oil industry in the late 2000's. DAS cannot measure absolute strain or temperature; the optical phase shift of the Rayleigh backscattered signal only responds to changes in strain and temperature. DAS is extremely sensitive with the potential to resolve strain changes on the order of 1 picostrain and temperature changes under 1 °µC (Leggett et al. 2021). Sampling rates of 10,000-16,000 Hz are typical for fibers in wellbores. The high sampling rates and strain sensitivities enable detection of acoustic signals. The spatial resolution of the measurements depends on the gauge length, which is on the order of 3 – 10 meters. Moving averages of the DAS phase shift are reported at 1-meter intervals.

Stimulation Diagnostics

The first SPE papers demonstrating DAS applications in oil and gas wellbores were not published until 2010 (Hull et al. 2010, Mullens et al. 2010). Almost immediately upon its emergence in the petroleum industry, DAS technology was applied to diagnose multistage hydraulic fracture completions in horizontal wells (Molenaar et al. 2011). **Figure 7** displays a heat map of acoustic energy measured by DAS during a single, four-cluster, hydraulic fracture stage from a well completed in the Marcellus Shale (Pakhotina et al. 2020). This representation of DAS data is known as a waterfall plot. The four green triangles on the depth axis mark the location of perforation clusters, and the red square indicates the plug setting depth. From the measured acoustic intensity it is evident that cluster 1 (closest to the plug) received a lower quantity of injected fluid than cluster 3, with clusters 2 and 4 receiving intermediate amounts of the injected fluid. The beginning and end of the acoustic signals at approximately 30 and 140 minutes correspond to the start and end of injection.

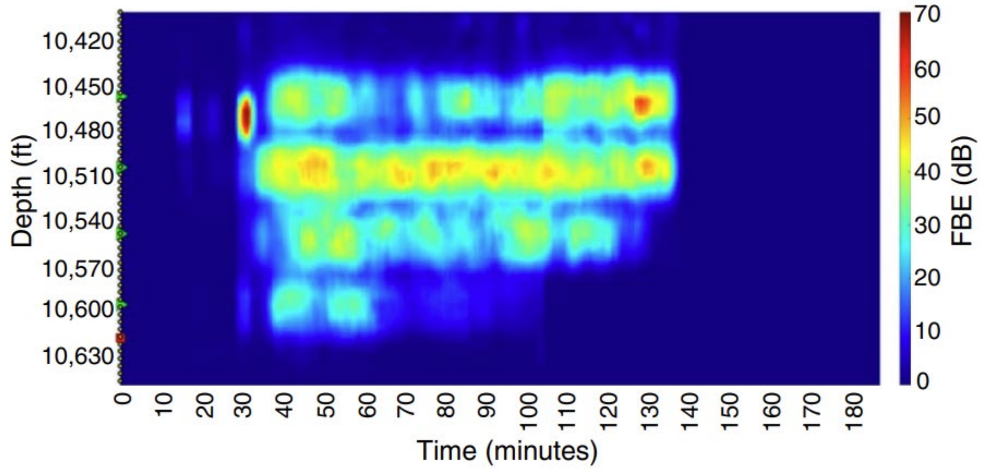

Figure 7 – Waterfall plot showing noise intensity generated by four perforation clusters during injection of a hydraulic fracture slurry. Each of the four clusters appears to be receiving fluid, but not in equal quantities. (Pakhotina et al. 2020).

Operators have used DAS measurements during stimulation to characterize fluid distributions of thousands of hydraulic fracture stages, leading to crucial insights on optimal perforation and treatment designs. Perhaps most significantly, DAS has revealed the importance of limited-entry perforating to maximizing the percentage of clusters that are adequately stimulated (Vissotski et al. 2021). In addition, DAS and DTS diagnostics during hydraulic fracturing have both revealed significant amounts of prior stage communication: treatment fluid intended for one stage leaking to a previously completed stage. An example of prior stage communication in an Austin Chalk completion is exhibited in **Figure 8**. Acoustic intensity recorded by DAS indicates that most of the treatment fluid meant for clusters above 15,500 feet entered perforation clusters below 16,250 feet. DAS is a useful diagnostic tool to evaluate different types of plugs and the stage isolation they achieve at downhole conditions.

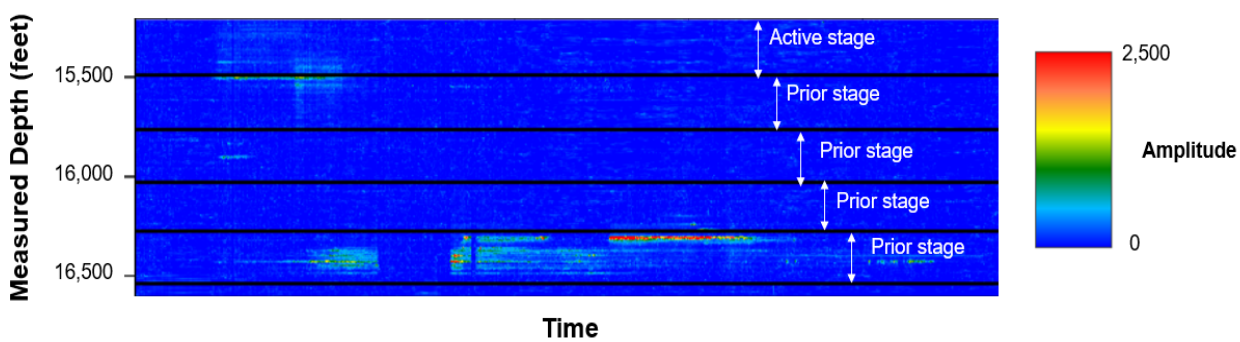

Figure 8 – Noise at the plug locations indicates leakage resulting in prior stage communication. Adapted from (Leggett et al. 2023).

Frac Hit Diagnostics

The previous examples demonstrate the ability for DAS to measure acoustics for flow diagnostics. For acoustic measurements, low-frequency changes in DAS due to static strain and temperature changes are filtered out. The next example showcases the strain-sensing capability of low-frequency DAS. **Figure 9a** shows a sensing configuration where a fiber is cemented outside the casing of a well offset to a well undergoing a hydraulic fracture treatment. The low-frequency component of DAS responds to strain changes induced along the offset well by propagating hydraulic fractures emanating from the treatment well. **Figure 9b** exhibits strain and strain-rate waterfall plots showing the characteristic pattern of converging tensile strain (yellow) surrounded by compressive strain (blue). Laboratory experiments and modeling have confirmed that these converging signatures indicate the approach of a propagating fracture and its eventual intersection of the offset well, or a frac hit (Leggett et al. 2022, Leggett et al. 2021).

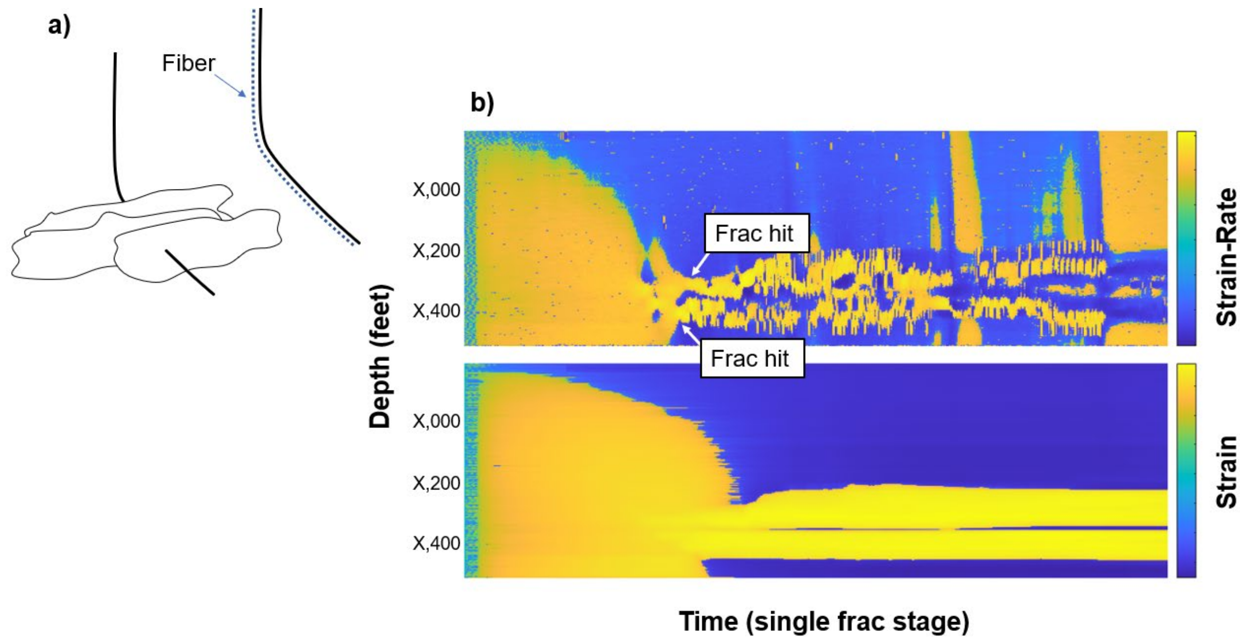

Figure 9 – Cross-well low frequency DAS strain sensing shows the arrival of fractures at the monitor well. Tension is positive (yellow) and compression is negative (blue). Adapted from (Leggett et al. 2022).

The strain waterfall plot is obtained by integrating the DAS-measured strain-rate. Other distributed strain sensing (DSS) techniques show similar responses. The timing and location of frac hits are useful to characterize hydraulic fracture dimensions and azimuths. Fracture characterization then informs well spacing and completion design decisions. Furthermore, operators have determined that the volume injected to the first frac hit, or the "volume to first response", serves as a proxy for cluster efficiency at the treatment well (Haustveit et al. 2020). If the total injection rate is distributed uniformly among the perforation clusters, the fracture arrival at the monitor well should take longer than if most of the fracture fluid is injected into only one or a few of the clusters. The volume to first response has been used extensively to inform the effectiveness of completion designs and the effects of depletion and parent-child interactions on hydraulic fracture geometry.

Gas Lift Monitoring

DAS has proven useful for other areas of production and operations engineering besides hydraulic fracture completion characterization. **Figure 10** displays a waterfall plot of acoustic energy during gas lift injection (Hemink and van der Horst 2018). In this field case, the fiber was installed on the production tubing. The noises at 850-, 1450-, 2150-, and 2750-feet are generated from flow through gas lift valves and indicate multipointing in this well. Traditionally, multipointing is diagnosed from analysis of the injection pressure, producing rates, and flowing temperature and pressure surveys. Direct measurement of noise through gas lift valves provides a simpler way of diagnosing gas lift valve malfunction.

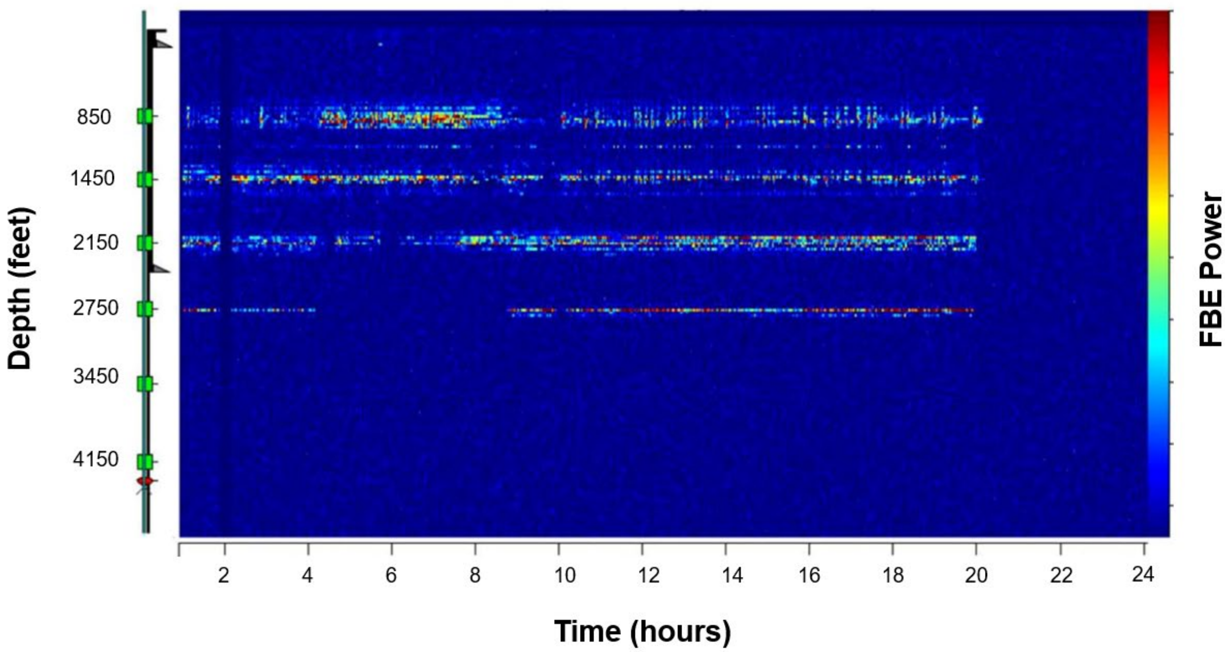

Figure 10 – Multipointing identified by noise on DAS waterfall plot. Adapted from (Hemink and van der Horst 2018).

Production Profiling

Finally, DAS can be used in some cases to serve as a multiphase production logging tool. Flow disturbances cause sound waves to propagate along the tubing or casing. Because the speed of sound varies between water, oil, and gas phases, measurements that track the speed of sound correlate to diagnosing the percentage of various phases. **Figure 11** shows waterfall plots of the acoustic energy generated by a pressure wave along a pipe (Naldrett et al. 2018). Figure 11a shows a single slope corresponding to the sonic velocity of a single phase fluid, where Figure 11b shows two slopes corresponding to the sonic velocities of water and gas. Differences in the upgoing and downgoing sound waves are used to quantity fluid velocity via the Doppler effect.

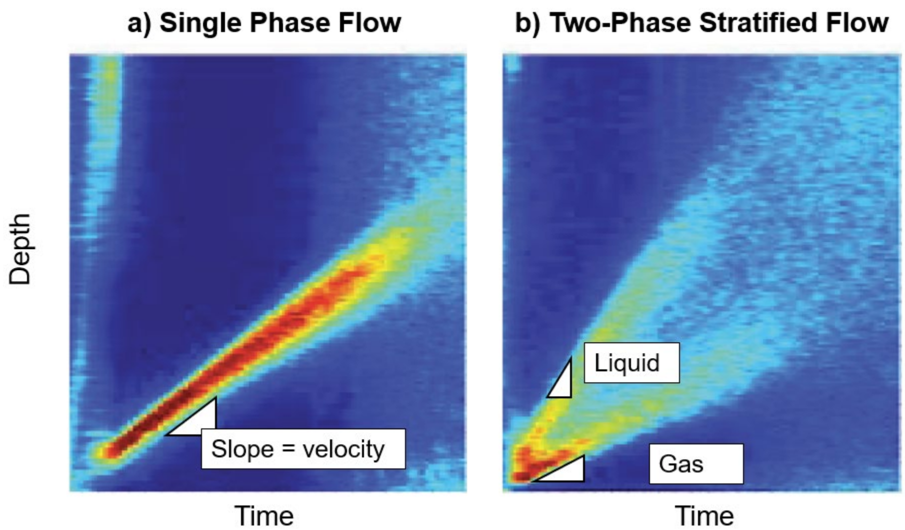

Figure 11 – Flow disturbances cause sound waves to propagate detectable by DAS. Waterfall plots are shown for a) Single phase and b) Two-phase gas-water flow. Adapted from (Naldrett et al. 2018).

The DTS and DAS case studies presented thus far are not an exhaustive list of uses for DFOS in oilfield production and operations. However, they provide a general sense of the diagnostic capabilities of DFOS using temperature, strain, and acoustic sensing. Innovation in fiber optic sensing is increasing the versatility of DFOS in oil and gas operations. In the next section, we briefly speculate about future relevant DFOS technologies.

FUTURE – DEVELOPMENT OF DISTRIBUTED PRESSURE AND CHEMICAL SENSORS

Distributed pressure and sensing (DPS) and distributed chemical sensing (DCS) technologies are under development that may prove useful to oil and gas operators. **Figure 12** demonstrates how a fiber optic strain sensor can be wrapped around a compressible material to translate a pressure disturbance to a strain response. In addition, fiber optic cables can be embedded in chemical-sensitive coatings that register a strain or temperature response when exposed to a certain chemical. Such cables exist today but they have not been adopted in the oil and gas industry, at least in any significant extent, to the author's knowledge.

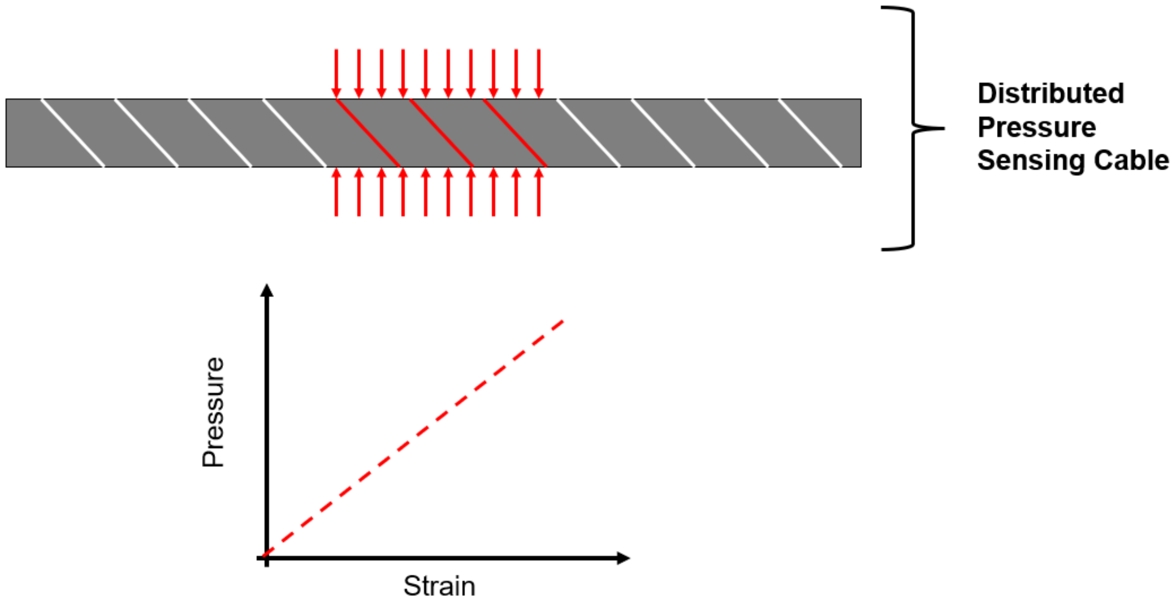

Figure 12 – Possible configuration to achieve distributed pressure sensing.

CONCLUSIONS

A literature survey has revealed the following applications for distributed fiber optic sensing in oil and gas production and operations:

- Gas lift surveillance
- Stimulation (acid and fracture) diagnostics
- Production and injection profiling
- Leak detection

The distributed temperature, strain, and acoustic sensing capabilities of fiber optic cables serve as useful diagnostic tools for the oil and gas industry. It is yet to be seen if distributed pressure and chemical sensing technologies will emerge as useful oilfield diagnostic tools.

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