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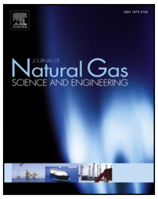

Fiber optic distributed sensing technology for real-time monitoring water jet tests: Implications for wellbore integrity diagnostics

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ABSTRACT

Distributed fiber optic sensing (DFOS), a rapidly evolving fiber-optic based technology for permanent well-based and geophysical monitoring for CO_2 geological storage (CGS) has attracted more attentions to investigate in multiple scales. In this study, two field trial wells were drilled, one well with 300 m depth in Mobara and the other well with 880 m in Ichihara, Japan and DFOS cables were deployed behind well casings. High-pressure water jet tests are performed at constant location of 127 m depth and at changeable jet locations with 1.33 m/min and 0.51 m/min pulling speeds in the 300 m well. Then, this DFOS system was utilized to monitor the water jet along the entire length of the 880 m well with 1.2 m/min descending speed. The temperature profiles induced by water jet could be real-time monitored and analyzed the cementing quality to further evaluate the wellbore integrity. The results show that the temperature abnormal zones have a good reverence with poor cementing in the two wells, which compared well with geophysical well logging data. Therefore, permanently installed DFOS wells will enable an efficient and simpler tool to diagnose the wellbore integrity for the CGS monitoring projects via the field water jet tests.

1. Introduction

CO_2 geological sequestration (CGS) into deep saline aquifers has been recognized as an effective and widespread option for mitigating greenhouse gas (GHG) emission throughout industry-scale CGS projects (Benson and Cook, 2005). For the safety of CO_2 storage, injected CO_2 must be trapped underground and not allowed to leak to the surface. Well integrity is one of the essential issues because wells and annuli in cement can act as leakage pathways for CO_2 from the reservoir to the surface (Celia et al., 2005; Jenkins et al., 2012; Paterson et al., 2016; Vilarrasa and Carrera, 2015). Of the well components, the cement between the casing and formation will be the first material exposed to CO_2, and therefore, the state of the cement in a CO_2 rich environment has been studied (e.g., (Kutchko et al., 2007)). Because there are many different possible leakage pathways, it is necessary to use several methods to examine the condition of the casing and cement exposed to CO_2.

Existing sensor techniques used to evaluate the quality of the cement annulus, such as acoustic and ultrasonic logging (Nakajima et al., 2013), require active (re-)entry into the well after the cementing operation has been completed. Besides, there are no techniques currently available that can monitor in real-time what happens in the annular spaces during long-term CO_2 subsurface injection and storage (Arts and Vandeweijer, 2011). The fiber optic technology presented here was developed to allow for continuous, real-time and long-term monitoring of the well integrity throughout the full phases of the wells.

Distributed fiber optic sensing (DFOS) technology has been used in the oil and gas industry since the 1990's (Kamal, 2014). The most widely used ones are Distributed Temperature Sensing (DTS) in multimode fibers (MMF) and Distributed Acoustic Sensing (DAS) in single-mode fiber (SMF)/MMF. These techniques have been applied to different phases of drilling and production, including - but not limited to - borehole seismic surveys, cement evaluation, fracture monitoring, flow profiling, well integrity monitoring and well abandonment monitoring (Baldwin, 2014; Daley et al., 2013; Dou et al., 2017; Freifeld et al., 2014, 2009; Gage et al., 2013; Lindsey et al., 2017; Paterson et al., 2016). In some recent studies, an advanced distributed temperature and strain sensing (DTSS) system based on Brillouin and Rayleigh backscattering, was installed in a test well for CO_2 injection to monitor wellbore integrity based on the strain measurement (Xue et al., 2014; Xue and Hashimoto, 2017). Besides, the same DTSS system, equipped with a SMF, was used to evaluate the quality of cementation and the state of zonal isolation (Wu et al., 2017, 2016). In addition, researchers discussed that fiber optic sensors have been used to detect and monitor

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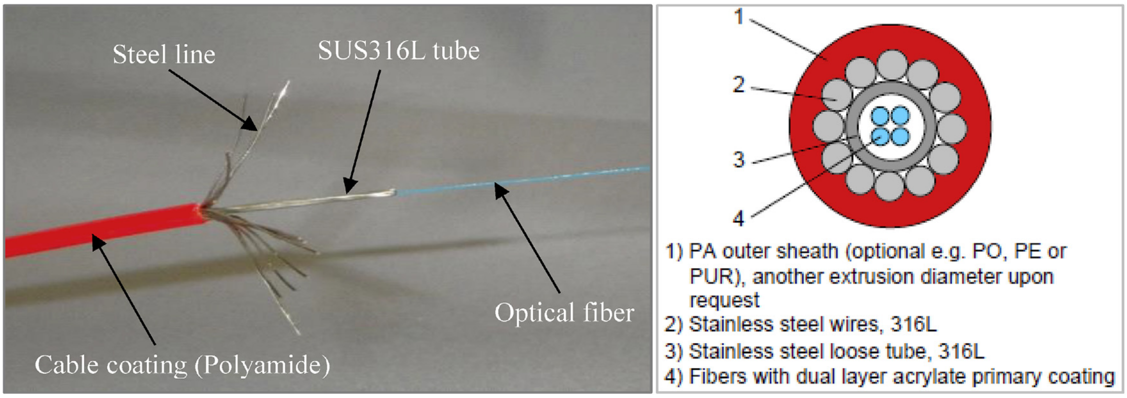

Fig. 1. The external assembly and the corresponding cross section of the optical fiber cable for the temperature measurement.

underground rock deformation and fluid flow from lab-experiments to field tests (Bhatia et al., 2014; Duguid, 2015; Gonzalez et al., 2012; Melo et al., 2015; Sun et al., 2017a, 2017b).

The primary objective of this study is to demonstrate the feasibility of DFOS technology to monitor the effects of the water jet on the temperature along the wellbore in the underground wells at the CGS sites. The measured results from DFOS deployed into two wells have a good agreement with the Electrical Micro Imager (EMI) and Radial Cement Bond Log (RCBL) data. Therefore, it is of great implications to permanently evaluate the wellbore integrity for the storage security of the CGS related projects in the deep reservoir formations.

2. Measuring principle of DFOS technology

Distributed fiber optic sensing technology is based on the generation of a narrow laser pulse and the travel time of the backscattered light to return to the detection unit in a fiber or cable. In this study, we use an advanced DFOS tool based hybrid Brillouin- Rayleigh sensing system. For this system, it is exciting to note that except for its unique superiorities mentioned earlier, it has a capability of precisely distinguishing influences from the distributed strain and temperature in one SM fiber, which is critically important to separate the two quantities in many engineering applications.

Therefore, Brillouin and Rayleigh frequency shifts $\varDelta\nu_R$ and $\varDelta\nu_B$ in this system can be expressed simply as a function of applied strain and temperature variations:

$$\varDelta\nu_B = C_{11}\varDelta\varepsilon + C_{12}\varDelta T \tag{1}$$

$$\varDelta\nu_R = C_{21}\varDelta\varepsilon + C_{22}\varDelta T \tag{2}$$

By combining equations (1) and (2), the strain and temperature can be separated by:

Table 1
The main specifications of the fiber optic cable used in this study.

Item	Component	Configuration
Optical fiber	Core	SMF
	Cladding	Acrylate resin
Strength material	Structure	SUS316L[a] tube + twined steel wires
	Steel wire	SUS316L[a]
	Tensile strength	100 kg
Cable coating	Material	Polyamide
	Temperature	85 °C
Cable dimension	Outer diameter	3.8 mm

[a] US316L is an austenitic stainless steel that contains 18% Cr, 12% Ni, 25% Mo, and less than 0.03% C (the "L" in 316L standing for low carbon) produced in Japan.

$$\begin{bmatrix}\varDelta\nu_B\\ \varDelta\nu_R\end{bmatrix} = \begin{bmatrix}C_{11} & C_{12}\\ C_{21} & C_{22}\end{bmatrix}\begin{pmatrix}\varDelta\varepsilon\\ \varDelta T\end{pmatrix} = \begin{bmatrix}C_{11} & D_{12}\\ C_{21} & D_{22}\end{bmatrix}\begin{bmatrix}\varDelta\varepsilon^{total}\\ \varDelta T\end{bmatrix} \tag{3}$$

where

$$C_{12} = D_{12} + \alpha C_{11} \tag{4}$$

$$C_{22} = D_{22} + \alpha C_{21} \tag{5}$$

and

$$\varDelta\varepsilon^{total} = \varDelta\varepsilon + \alpha\varDelta T \tag{6}$$

where α denotes thermal expansion coefficient, C_{11}, C_{12}, D_{12}, C_{21}, C_{22}, D_{22} stand for the strain-frequency, the temperature-frequency and the pure frequency-temperature coefficients of Brillouin and Rayleigh scattering, respectively.$\varDelta\varepsilon^{total}$ is the total strain, a sum of its mechanical and thermal components. For the selected coated fiber, Yamauchi has provided a simple and effective method for determining the coefficients in the laboratory experiments (Kishida et al., 2014).

3. Cable fabrication and field test description

Three kinds of fiber cables were deployed behind well casing, and the water jets were implemented along the wellbore at the two trial wells with 300 m and 880 m depths in Japan. The structure and configurations of the fiber cables used in the tests are shown in Fig. 1 and Table 1. In order to continuously measure the temperature in the depth direction with the borehole annulus, the fiber cable was custom-made to improve the coupling strength between casing and cement. As for the optical fiber in the cable, a silica-based SMF was used for the core and dual acrylate resin layer was made for the cladding. In order to improve the response speed and adhesion of the fiber, the coating was specially made with silicone resin instead of fluorine resin.

The optical fiber was mounted into a 316L stainless steel tube to detect strain and pressure. In addition, the number of the sensor was set to four in consideration of a spare for fiber breakage. The stainless steel tube was twined with steel wires to make it an armature to enhance its strength. Furthermore, it was coated with a polyamide resin (PA) outer sheath.

High-pressure water jet (HPWJ) is utilized to remove impurities of the wellbores by jetting high pressure water in the oil and gas field drilling. In this study, this technology is used to jet high-pressure water directly at an arbitrary depth of the two wells and thus to artificially change the temperature inside the wells. When the temperature of the wellbore varies, the high-sensitivity fiber cables deployed behind casing can capture the responses in the form of frequency shift, which can be converted to the temperature profiles of the wellbores. Ultimately, based on the profiles, it can be easy to assess the cementing quality and to further diagnose the wellbore integrity.

Water jet field test is mainly composed of rolling and pumping cars,