

Metallic Film-Coated Optical Fiber Sensor for Corrosion Monitoring at High Pressures

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ABSTRACT

It is important yet challenging to monitor and locate corrosion over long-distance natural gas pipelines, especially for internal corrosion. Water vapor condensation can provide an aqueous electrolyte for corrosion to occur inside the pipe. We have previously demonstrated distributed optical fiber-based corrosion and humidity sensors at ambient pressure. In this work, optical fiber sensors were interrogated using an optical backscatter reflectometer and tested under high pressures to simulate pressurized pipeline conditions. When pressurized to 900 psi with dry N₂, strains of single-mode optical fiber sections became more negative, indicating compressive strains along the fiber. Humidity was successfully monitored at 900 psi based on water-induced strain changes of the fiber polymer jacket. The corrosion sensor section was electrolessly coated with Fe thin film as the corrosion proxy. The backscattered light intensity didn't show noticeable responses in dry N₂, indicating that no corrosion occurred. When wet CO₂ gas pressurized the reactor to 850 psi, the backscattered light intensity increased in several locations on the Fe thin film within the first hour, indicating localized corrosion. When a small amount of water was introduced to the CO₂ pressurized reactor, the aqueous corrosion was also successfully detected.

Key words: Optical fiber sensor; Corrosion sensor; Humidity sensor; Pressure sensor; High pressures; Distributed sensing.

INTRODUCTION

Corrosion is a common and critical issue in the oil and natural gas industry and it adversely affects the component functionality and structural integrity of infrastructure for exploration, production, transportation, processing, and CO₂ sequestration. The natural gas delivery system includes 528,000 km (328,000 miles) of transmission and gathering pipelines in U.S.¹ According to the Pipeline and Hazardous Materials Safety Administration (PHMSA) database, corrosion has caused ~25% of the natural gas transmission and gathering pipeline incidents over the last 30 years in the U.S., and 61% out of corrosion-caused incidents were due to internal corrosion.²

It is challenging to monitor internal corrosion effectively as the inside of the pipeline is not readily accessible during regular inspections. Moreover, corrosion can occur at some random locations inside the pipelines which extend thousands of miles. Most existing sensor technologies such as corrosion coupons and electrical resistance probes are point sensors and cannot detect corrosion other than at the sensor installed locations. Pipeline inspection gauges (PIG) or in-line inspection tools (ILI) can inspect the whole pipe but they are costly and typically run every 5–7 years per regulatory requirements or company policies.³ Therefore, it is of significant value to have a sensor capable of real-time monitoring and locating internal corrosion inside the long-distance pipelines before the structural integrity is compromised.

As an emerging sensing technology, optical fiber based sensors have been studied to monitor corrosion and structural health monitoring (SHM) in recent years.^{3–6} Compared with other sensing platforms, the fiber optics platform has advantages such as non-invasive monitoring, in-situ measurements, small size, flexibility, geometric versatility, light weight, inherent immunity to electromagnetic interference, compatibility to optical fiber data communication systems, and improved safety in the presence of flammable gas environments when compared to electrical based sensors. A network of optical fiber sensors can realize a distributed sensor system for early corrosion onset and water detection over a long distance.^{7–11}

We have previously demonstrated a distributed corrosion sensor for early corrosion detection using an optical backscatter reflectometer (OBR), leveraging corrosion proxy sensing materials integrated with the optical fiber sensing platform that can provide insight into the corrosion inside the pipelines. The metallic coatings such as Fe and X65 carbon steel thin films have been demonstrated for optical fiber corrosion sensors based on light intensity or strain changes.^{6,11–13} Water vapor condensation at the cold spots can provide the aqueous electrolyte for corrosion to occur inside the pipe. The inherently existing acid gases inside the pipelines such as CO₂ and H₂S can dissolve in water, forming corrosive electrolytes.^{14–17} Therefore, we have also demonstrated a fully distributed optical fiber water/humidity sensor as an indicator for corrosivity and potential internal corrosion inside the pipelines. The intrinsic polymer jacket of the SM fiber is hygroscopic and can serve as a water sensing layer due to expansion/swelling from water absorption, and the water-induced strain can be interrogated by the OBR.^{10,18–20} Last year, we demonstrated a multi-parameter optical fiber sensor for simultaneous monitoring of corrosion and humidity with location information along the fiber under ambient conditions. Here, we present the results of distributed optical fiber sensors for corrosion and humidity/water monitoring under high pressures to validate the sensor applications in pressurized pipeline conditions.

EXPERIMENTAL PROCEDURE

High-Pressure Experimental Setup

A high-pressure stainless-steel (SS) tube reactor was constructed for sensor testing under high pressures, as shown in Figure 1. The main reactor chamber consists of a 1-meter SS tube with 1 inch (2.54 cm) outer diameter and 0.083 inch (0.21 cm) wall thickness. Gas flow of N₂ or CO₂ was controlled

with mass flow controllers or valves. Humidity was controlled using the water bubbler. All the tests were run at room temperature ($\sim 22\text{ }^{\circ}\text{C}$). The pressures used in this work were 900 psi for N_2 and 850 psi for CO_2 . Once the desired pressure was achieved, the humidity inside the reactor was controlled by changing the flow path from the dry gas line to the water bubbler line. To change the gas or humidity conditions inside the reactor, the vent valve at the end would be slightly opened to change gas and humidity throughout the reactor chamber while maintaining the pressures. At least 5 minutes of gas flow was used for switching gases and >40 minutes for changing the humidity inside the reactor.

The optical fiber sensors were inserted into one left end of the SS tube reactor using 1/16" (0.159 cm) ferrules (60% Vespel/40% graphite) with a 0.3-mm hole size as a sealant. The left end of the single mode fiber was connected to the OBR. The OBR provides a spatial profile of the backscattered light intensity and strain along the fiber, enabling distributed monitoring of corrosion and water/humidity. The fitting was tightened to achieve a suitable seal (<10 psi pressure change over 24 hours).

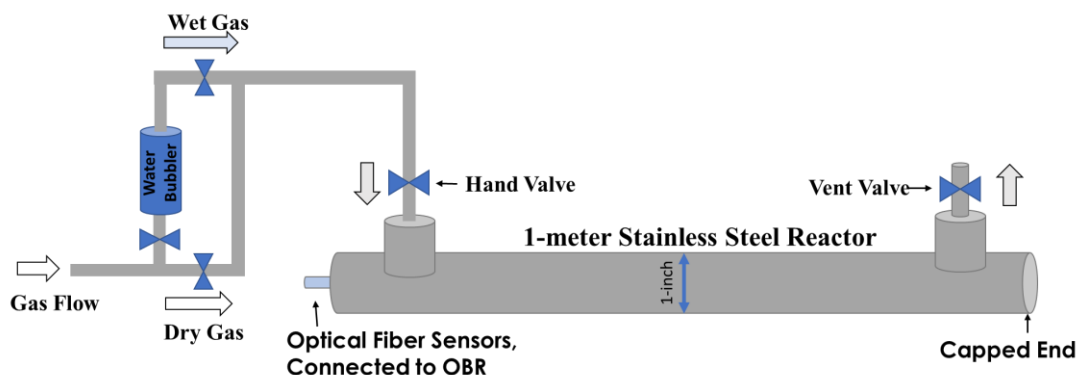


Figure 1: Schematic diagram of the experimental setup for distributed optical fiber measurements in a stainless-steel tube reactor under high pressures.

Preparation of Single-mode Optical Fibers as Humidity and Pressure Sensors

We have previously demonstrated fully distributed sensing of water and humidity using unmodified off-the-shelf SM optical fibers connected to an OBR.^{10,18} The intrinsic polymer jacket coating or dual acrylate coating of the SM fibers is hygroscopic and can serve as the water sensing layer due to expansion/swelling from water absorption (Figure 2a). The swelling-induced strain changes were interrogated with the OBR to enable fully distributed water monitoring. The strain-based H_2O sensor is sensitive to H_2O molecules regardless of the phase (liquid or vapor) or the surrounding media. When exposed to high pressures in the reactor, the SM optical fiber is subject to compressive stress due to the surrounding high-pressure environment (Figure 2b).

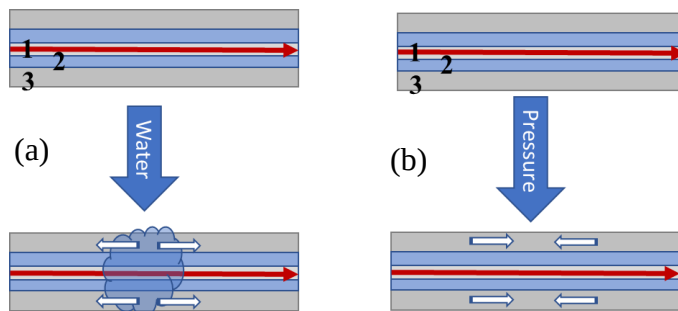


Figure 2: Sensing principles of optical fiber sensors for (a) water and (b) pressure monitoring. 1: single-mode fiber core; 2: cladding; 3: polymer jacket.

In this work, we prepared a multi-segment humidity sensor consisting of the following fiber sections spliced together (Figure 3a): 20 cm of SMF-28 Ultra fiber, 20 cm of SMF-28 Ultra fiber with polymer jacket removed, and 15 cm of SMF-28 fiber. Without the polymer jacket, the unjacketed section does not exhibit water sensitivity, but is sensitive to other environmental parameters such as temperature and pressure, acting as a reference to compensate for temperature and pressure effects. Additionally, the two different types of SM fibers allow for differentiation of strain and temperature effects during OBR measurements. The SMF-28 Ultra optical fiber has a dual acrylate coating, which can protect the fiber against microbending-induced attenuation. The inner primary coating is soft with a low modulus which can cushion and protect the fiber from external stress, whereas the outer primary coating is hard and tough.^{21,22}

After the multi-segment humidity sensor was inserted into the SS tube reactor and sealed properly, dry N₂ gas flow of 200 sccm was used to dry the polymer jacket from atmospheric humidity to 0% RH at 1 atm. A new reference of strain profile was set at 0% RH and 1 atm for the following strain measurements. The pressure was then raised to 900 psi with dry N₂ to observe the pressure effect. Lastly, the N₂ gas was redirected via the water bubbler to change the humidity to 100% RH at room temperature.

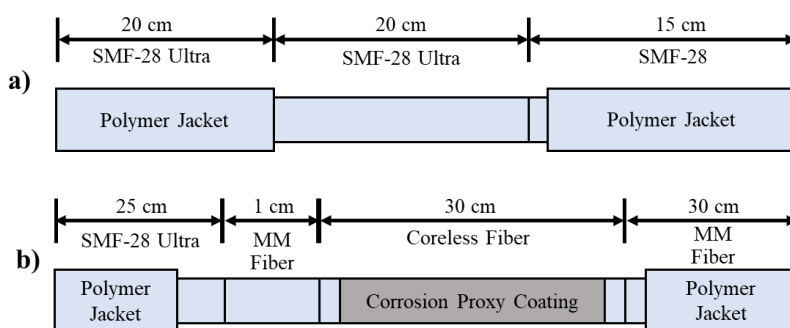


Figure 3: Schematic diagram of the spliced optical fiber sensor configurations for (a) humidity and pressure, and (b) corrosion monitoring inside the SS tube reactor.

Preparation of Metallic Thin Film-Coated Optical Fiber Corrosion Sensor

The optical fiber corrosion sensor was prepared using a metallic corrosion proxy material. The Fe thin film was deposited through an electroless plating process. Before the deposition, the polymer jacket was stripped off the coreless fiber section which was then cleaned with isopropyl alcohol. Then, it was spliced with multiple-mode optical fibers at the two ends.

Iron coated optical fibers were prepared using a previously described electroless plating recipe.¹¹ Briefly, the coreless fiber section was sensitized in a solution consisting of 22.6 g/L tin(II) chloride (SnCl₂, 98%) and 10.0 mL/L hydrochloric acid (HCl, concentrated) for 30 seconds. The coreless optical fiber section was then activated by immersion into a solution consisting of 0.795 g/L of palladium(II) chloride (PdCl₂, 99%) and 5.00 mL/L HCl for 30 seconds. A repeated step of sensitization and activation was found to improve the plating, and the fiber section was then rinsed in DI water and dried under nitrogen. The coreless section of fiber was then submerged in a plating bath consisting of 11 g/L FeSO₄·7H₂O, 57 g/L C₆H₅Na₃O₇·2H₂O, 3.0 g/L NaBH₄, and 10 g/L H₃BO₃. The pH of this solution was adjusted to 9.8 with 1.2 M NaOH. After 1-2 minutes of plating, the fiber was taken out and ready to be used for corrosion tests.

Similar to our previous work at the ambient pressure,²³ a multi-parameter optical fiber sensor was prepared through combining the water/humidity sensor and the corrosion sensor by splicing the following optical fiber sections (Figure 3b): 25 cm of SMF-28 Ultra fiber, 1 cm of multi-mode fiber, 30 cm