

Paper No.
16909



Multi-parameter Optical Fiber Sensor for Simultaneous Corrosion and Humidity Monitoring

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ABSTRACT

For long-distance natural gas pipelines, it is important to monitor and locate corrosion events, especially for internal corrosion. Water vapor condensation can provide aqueous electrolytes necessary for corrosion to occur inside the pipe. Based on previous work, a multi-parameter optical fiber sensor was developed and demonstrated for simultaneous monitoring of corrosion and water/humidity with location information along the fiber. Corrosion was detected through light intensity changes associated with the corrosion proxy coating and the presence of water was monitored based on water-induced strain changes on the optical fiber. The multi-parameter sensor was tested in both aqueous (acidic solution) and humid gas (N_2 or CO_2) conditions. As the humidity varied between 0% relative humidity (RH) and 100%RH, the single-mode fiber section showed water sensing capability with good reversibility and sensitivity. The corrosion sensor didn't show cross-sensitivity to humidity. In corrosive conditions, the corrosion sensor showed an increase in the backscattered light intensity at corroded locations because light absorption of the metallic thin film decreased as the film was corroded. Importantly, the corrosion sensor was able to monitor localized corrosion in wet CO_2 gas, which is

representative of internal corrosion in natural gas pipelines. The XPS (X-ray photoelectron spectroscopy) results indicate formation of iron carbonate after wet CO₂ corrosion.

Key words: Corrosion sensor; Water/humidity sensor; Multi-parameter optical fiber sensor; Distributed sensing; Pipeline corrosion; CO₂ corrosion.

INTRODUCTION

Corrosion is a critical issue in the oil and natural gas industry because 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.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, and 61% of the corrosion-caused incidents were due to internal corrosion.^{2,3} The ability to detect early corrosion onset in real time before the structural integrity is compromised can have a significant impact on preventing catastrophic failures of infrastructure resulting from corrosion.

Water vapor condensation can provide aqueous electrolytes for corrosion to occur inside the pipe. The inherently existing acid gases such as CO₂ and H₂S could dissolve in water forming corrosive electrolytes.⁴⁻⁷ Despite the upstream gas dehydration treatments, liquid water can form due to water vapor condensation at cold spots or may be introduced to the natural gas pipes due to plant upsets.⁸ Because water is a key parameter that initiates and sustains corrosion, water detection can serve as an early indicator for potential internal corrosion inside the pipeline.

It is of crucial importance to monitor and locate corrosion events for long-distance natural gas pipelines, especially for internal corrosion. However, it has been challenging to monitor internal corrosion effectively as the inside of the pipeline is not readily accessible during regular maintenance and inspection. Moreover, corrosion is a localized phenomenon that can occur at random locations yet pipelines extend for thousands of miles. Locating corrosive spots or localized corrosion can facilitate further inspection and effective mitigation of corrosion before catastrophic failures occur. As an emerging sensing technology, a network of optical fiber sensors can realize a distributed sensor system for early corrosion onset and water detection over a long distance.⁹⁻¹³ The optical fiber sensors can be deployed inside the pipeline to monitor internal corrosion, which can be installed at the top and/or bottom of the pipe or any position of interest along the whole pipe.

We have previously demonstrated a distributed corrosion sensor for early corrosion detection and a fully distributed humidity sensor using an optical backscatter reflectometer (OBR). The corrosion sensor involves use of corrosion proxy materials integrated with an optical fiber sensing platform that corrode at a rate which provides insight into corrosion inside the pipelines. Metallic coatings such as Fe and X65 carbon steel thin films have been demonstrated for optical fiber corrosion sensors based on either light intensity changes or strain changes.¹³⁻¹⁶ The fully distributed optical fiber water/humidity sensor consists of a commercial off-the-shelf single-mode (SM) optical fiber connected to an OBR (distributed sensing with an OBR can be found in References 3,17). The intrinsic polymer jacket of the SM fiber is hygroscopic and can serve as the water sensing layer due to expansion/swelling from water absorption, and the water-induced strain can be interrogated by the OBR.^{12,18-20}

In this work, a multi-parameter optical fiber sensor was developed and demonstrated for simultaneous monitoring of corrosion and humidity with the location information along the fiber. The multi-parameter sensor was tested in both aqueous (acidic solution) and humid gas (N₂ or CO₂) conditions to monitor corrosion and humidity simultaneously.

EXPERIMENTAL PROCEDURE

Metallic Thin Film Coated Optical Fiber Corrosion Sensor

For the corrosion proxy materials, two types of metallic thin film coatings were prepared on the coreless fiber section of the optical fiber sensor. One type was a 100 nm thick X65 carbon steel thin film which was sputter deposited. The other type was the Fe thin film deposited through an electroless plating process. Before the deposition, the polymer jacket was stripped off of the coreless section, which was then cleaned with isopropyl alcohol. Then, it was spliced with multiple-mode optical fibers at the two ends to be prepared for later use.

X65 carbon steel thin film coated fibers were prepared as described in the authors' previous work.¹⁴ Briefly, the 100 nm X65 thin film was deposited with a plasma sputter deposition system using a direct current (DC) power source. A sputtering target was made of Grade X65 which meets American Petroleum Institute (API) 5L specification for pipeline steel. The optical fiber was held by a custom-made fixture connected to a rotator inside the sputtering chamber to achieve a uniform thickness around the fiber. The sputtering was run at room temperature, 50 W DC, and 3 mTorr chamber pressure with a 12 cm sputter distance using Ar as the process gas. The target was pre-sputtered for 20 min to remove undesired contamination on the surface prior to deposition.

Iron coated optical fibers were prepared using a previously described electroless plating process.¹³ Briefly, the coreless fiber section was sensitized in a solution consisting of 22.6 g/L tin(II) chloride (SnCl_2 , 98%) and 10.0 mL/L hydrochloric acid (HCl, concentrated) for 30 seconds. The coreless fiber section was then activated by immersion into a solution consisting of 0.795 g/L of palladium(II) chloride (PdCl_2 , 99%) and 5.00 mL/L HCl for 30 seconds. A repeated sensitization and activation was found to improve plating, and the fiber section was then rinsed in DI water and dried under nitrogen. The coreless section was then submerged in a plating bath consisting of 11 g/L $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$, 57 g/L $\text{C}_6\text{H}_5\text{Na}_3\text{O}_7 \cdot 2\text{H}_2\text{O}$, 3.0 g/L NaBH_4 , and 10 g/L H_3BO_3 . The pH of this solution was adjusted to 9.8 with 1.2 M NaOH. After 1-2 minutes, the fiber was removed from the plating bath and was ready to be used for corrosion tests.

Single-mode Optical Fiber as a Water Sensor

It has been found that an unmodified off-the-shelf SM optical fiber connected to an OBR was capable of fully distributed sensing of water.^{12,18} The intrinsic polymer jacket coating (dual acrylate coating) of the SM fiber is hygroscopic and can serve as a water sensing layer due to expansion/swelling from water absorption. The swelling-induced strain change is interrogated with the OBR to enable fully distributed water monitoring. This strain-based H_2O sensor is sensitive to H_2O molecules regardless of the phase (liquid or vapor) or the surrounding media.¹² The SM optical fiber used in this work 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}

Multi-parameter Sensor and Experimental Setup

A multi-parameter optical fiber sensor capable of monitoring both water/humidity and corrosion simultaneously was prepared by combining the water sensor and corrosion sensor, and it was connected to and interrogated by an OBR. Corrosion was detected through the light intensity changes associated with the corrosion proxy material, and water/humidity was monitored based on the water-induced strain changes on the optical fiber. The multi-parameter sensor was constructed by splicing the optical fiber sections in the following order: 2 meters of the SM fiber, a 6-cm section of multi-mode fiber, a 12-cm section of metallic film coated coreless fiber, and a 50-cm section of multimode fiber. The

multi-parameter sensor was connected to an OBR via the SM fiber end. A schematic of this fiber setup is shown in Figure 1.

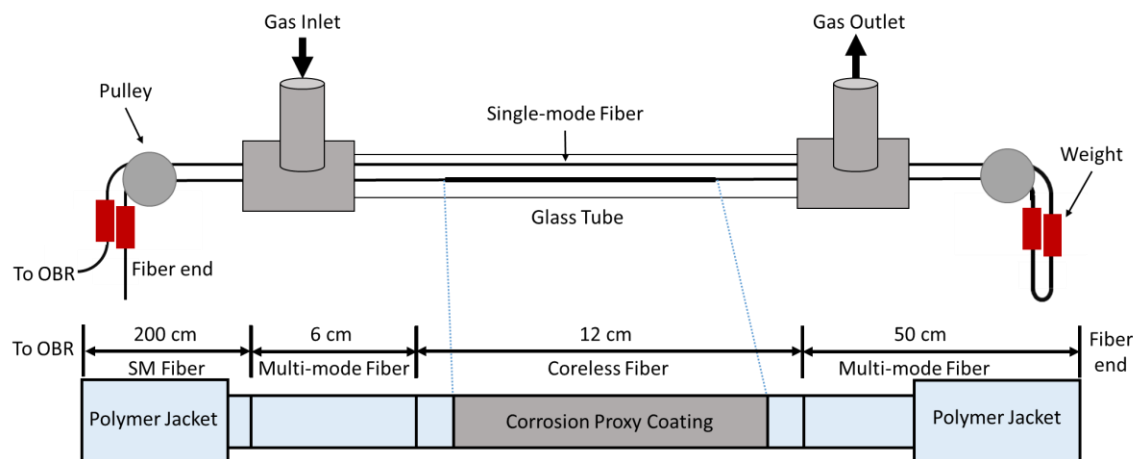


Figure 1: Schematic diagram of the spliced optical fiber sensor configuration and the experimental setup for distributed measurements in a glass tube.

As illustrated in Figure 1, the spliced optical fiber was placed in a glass tube (diameter of 1.5 cm, ~30 cm long). The fiber was looped back through the glass tube setup so that a section of the jacketed SM fiber (water sensor) and the metallic film coated coreless fiber section (corrosion sensor) were positioned inside the glass tube. The fiber directly outside each end of the tube was wrapped around a pulley (about 40 cm from one pulley to the other). Weights (9.77 g each) were clipped on each end of the two fiber sections to keep the fiber straight and ensure a controlled tension was placed on each fiber section in the glass tube. The left end of the SM fiber was connected to the OBR. The OBR provides a spatial profile of the backscattered light intensity and strains along the fiber, enabling distributed monitoring of corrosion and water/humidity.

The multi-parameter sensor was tested in both aqueous (HCl solution, pH 3) and humid gas (N₂, CO₂) conditions to monitor corrosion and water humidity with location information. For the strain measurements, the fiber was first stabilized with weights, and the strain profile along the fiber with weights was set as the new reference. Then, dry nitrogen was flowed through the glass tube at a rate of 100 sccm until the fiber polymer jacket was observed to be completely dry. Next, the same nitrogen flow was bubbled through water causing the humidity in the glass tube to increase to 100% relative humidity (RH). Alternatively, nitrogen was exchanged for CO₂ through the bubbler to simulate wet CO₂ corrosion. The HCl solution was also used to simulate conditions leading to mass loss caused by corrosion. A new strain reference was reset for each change in condition.

RESULTS

Simultaneous Monitoring of Water and Aqueous Corrosion

Each measurement from the OBR provides a spatial profile of both light intensity and strain simultaneously along the fiber with location information. Therefore, the two sections of optical fiber were able to detect corrosion and water simultaneously inside the glass tube.

Figure 2 shows the measurements of light intensity amplitude (dB/mm) and the strain, respectively, when the humidity was changed from 0%RH to 100%RH N₂. The blue block in the upper figure highlights the SM optical fiber length within the glass tube (~30 cm) as the humidity sensor, and the strain increased by ~125 $\mu\epsilon$ due to water-induced swelling of the polymer jacket of the SM fiber. It took ~50 min for water absorption in the polymer jacket to be stabilized. The gray block in the lower figure