

Testing of a Low-Power Wireless Sensor Network of Conductivity Probes for the Detection of Corrosive Fluids in Pipelines

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ABSTRACT

A low powered wireless sensor network was developed to detect corrosive fluids in pipelines located in remote locations. This paper describes the testing of the four-electrode probe prototype to detect the presence of corrosive fluids in pipelines. This probe was coupled with an Arduino⁺, programmed to output conductivity readings using the voltage difference across the electrodes. A heating module was constructed to model the temperature gradient encountered across the insulation of a hot (insulated) pipeline. This unit was used to explore the viability of thermoelectric power generation as a local energy source. The conductivity probe was tested in a flow cell connected to a peristaltic pump to simulate active pipeline conditions which includes different fluid velocities, temperature, and presence of oil. Results indicate that conductivity probes are able to function effectively in the presence of a flowing oil-water mixture as long as the flow was sufficiently turbulent to avoid stratification of the oil-water phases. Thermoelectric generation was determined to be a non-viable local power source for the modules. An alternative photovoltaic solar source with battery storage was determined to be the best alternative. An ultra-low-power binary galvanic continuity probe was designed and tested to further reduce power consumption and to help detect electrode fouling.

Key words: remote sensing, wireless sensor networks, on-line conductivity measurement, remote, arctic climate

INTRODUCTION

Water and internal corrosion in oil and gas process streams

Internal corrosion presents a significant threat to metallic piping and pressure vessels in the upstream oil and gas sector. In the U.S., the cost of corrosion in transmission pipelines has been estimated to be \$7B per year [1]. A comprehensive analysis of pipeline failures in Alberta Canada between 1990 and 2005 found that internal corrosion was responsible for 58% of failures [2]. In order for corrosion of metallic materials to occur, an ionic conductor (electrolyte) must be in contact with the surface of the material. The process streams found in upstream oil and gas are varied. Piping and pressure

⁺ Trade Name

vessels are expected to be exposed internally to multiphase mixtures (oil, water, and natural gas), water (for secondary recovery), produced water, separated oil (with residual water), wet natural gas, and dry natural gas, and concentrated chemicals used for corrosion inhibition and reservoir stimulation [3-5]. Chemical species present in these fluids include gasses, most notably oxygen, carbon dioxide, and hydrogen sulfide, as well as inorganic and organic acids [5,6]. The internal corrosion rates and mechanisms are determined by the concentrations of these species, the pipeline / vessel material, and the operational conditions (e.g., temperature, pressure, velocity, etc.) [5-9].

Produced hydrocarbons, including crude oil, are poor electrolytes and do not, by themselves, present a corrosion threat. The water produced along with these hydrocarbons is an electrolyte and drives internal corrosion processes in production fluid streams. The distribution of the oil, gas, and water phases, and the extent of their mixing/stratification, is determined by the flow conditions and composition of the stream [10]. This distribution has a strong impact on the corrosion rates and mechanisms in multiphase process streams [5,6]. In general, corrosion processes become more aggressive as the percentage of electrolyte (produced water) increases [5]. Operators rely extensively on corrosion inhibitors to control internal corrosion in carbon steel vessels. These cocktails of chemicals are specifically tailored to the composition and operating conditions (e.g., flow regime, composition, temperature, etc.) of a particular process stream. In order for inhibitors to be effective, they must be present in sufficient concentrations [5,6].

In practice, the geometry of piping and pressure vessels may undermine the effectiveness of corrosion inhibition strategy. Regions of local flow stagnation (e.g. dead legs) and low spots may encourage the accrual of the water phase (in multiphase systems) [12]. In inhibited process streams, there may be insufficient mass transport of inhibitor to the accrued electrolyte volume to produce sufficient corrosion inhibition. Streams that contain very little electrolyte (e.g. separated oil and dehydrated gas), may be deemed non-corrosive and left uninhibited. In these systems, the aforementioned geometric features can lead to the accrual of significant volumes of electrolyte and concomitant corrosion processes at said locations. The ability to detect the localized accrual of electrolyte in-situ and in real time is advantageous. The primary challenge to this effort is the large number and wide spatial distribution of these potential electrolyte accrual locations. To be effective, any monitoring solution must provide a cost-effective method of powering and communicating with sensors at these locations.

Internal corrosion monitoring

In the upstream oil and gas sector, internal corrosion is monitored using a suite of techniques. The most common of these can be broadly categorized as: Non-destructive Inspection (NDI), corrosion coupon (CC), and Electrical Resistance (ER) probes. NDI techniques include ultrasonic testing (UT), magnetic flux leakage (MFL), radiographic testing (RT), acoustic emissions testing (AET), and eddy current testing (ECT) [13]. Several of these techniques are frequently utilized during In-line Inspection (ILI) to collect corrosion data along the length of a pipeline [13]. Others, are better suited for sampling at discrete test locations. In either case, these inspections are performed periodically in order to verify that corrosion processes are being mitigated effectively.

Corrosion coupons (CC), also known as weight loss coupons, are inserted into the process stream via hydraulic access fittings. The coupons are made of a similar material as the pipeline or vessel and thus, are used to obtain an approximation of the internal corrosion processes occurring on the structure. The coupons are exposed for 1-6 months and then retrieved. The average corrosion rate is then determined from the mass lost during the exposure period [14-16].

ER probes contain a resistive element made from a material similar to that of the structure. The resistive element is inserted into the process stream via a hydraulic access fitting, where it undergoes corrosion and loses volume. As the cross-sectional area of the resistive element is reduced, its electrical resistance increases. The probe is calibrated to provide a direct relation between this change in resistance and the corrosion rate of the resistive element [3]. ER probes have a high-level of sensitivity and can provide short-term (hourly) estimates of internal corrosion rates.

Linear Polarization Resistance (LPR), Electrical Impedance Spectroscopy (EIS), and Zero-resistance Ammetry (ZRA) are occasionally utilized in the upstream oil and gas industry, however fluid conductivity requirements largely limit (or preclude) their deployment in multiphase fluids, natural gas, and crude oil [17].

Role of monitoring in corrosion management

CCs and ER probes are installed at hydraulic access fittings which allow for installation and retrieval without disrupting operations [18]. ER probes are attached to data logger which may, or may not be integrated into a Supervisory Control and Data Acquisition (SCADA) system to provide real-time monitoring. In many cases, the ER data is retrieved periodically via a physical or wireless interface with the data logger. ER probes tend to be installed close to existing infrastructure (buildings) to facilitate the periodic retrieval of data and to provide cost-effective access to grid power. CC's do not require electrical power; however, they must be periodically retrieved/replaced. As such, CC's are often installed in easy-to-access locations. This is especially true in remote arctic locations, where access to pipelines and vessels is limited.

In general, ER probes are used to determine the effect that short-term changes in system parameters and inhibitor dosing rates have on internal corrosion rates. CC's provide a longer-term average picture of system corrosion rates, while also providing some insight into corrosion mechanisms. NDI techniques provide a reality check on the long-term success of corrosion mitigation strategies. ILI provides near-complete coverage of piggable pipelines, while discrete sampling at known problem locations delivers a high-resolution picture of internal corrosion processes.

Limitations of current monitoring technology

CCs and ER probes are limited primarily by their lack of complete system coverage. The corrosion rates and mechanisms at the installation locations may not be representative of the system. Localized conditions (such as the aforementioned accrual of electrolyte) are unlikely to be captured. For onshore installations, in arctic climates, the majority of pipelines are above ground and insulated. In these locations, the increased accessibility associated with above-ground infrastructure is countered by the additional challenges poised by insulation, lack of roads, lack of utilities, rugged terrain, and extreme weather. While ILI techniques provide near complete systems coverage, they can only be deployed on piggable pipelines. In addition, ILI techniques are less sensitive than discrete (manual) NDI measurements, and are likely to miss internal corrosion in occluded locations (e.g. dead legs). Discrete NDI measurements are greatly restricted by the impediments to access previously listed for ER probes and CCs.

The corrosion monitoring strategies currently employed in the upstream oil and gas sector have proven to be reasonably effective and reliable, however, electrolyte accrual at occluded locations continues to produce "blind spots" in corrosion monitoring programs. Operators are well aware of the risk that these locations pose and have committed significant resources to inspecting and/or eliminating (via physical modification) these sites. The common element across all multi-phase and gaseous process streams is the accrual of electrolyte. While the present work is primarily focused on internal corrosion, it should be noted that the accrual of electrolyte is also precedes corrosion under insulation (CUI), an external damage mechanism that is pervasive in insulated tanks and pipelines. The detection of electrolyte accrual is therefore the focus of this work. Specifically, the authors will describe the testing of conductivity-based sensors integrated into a low-power wireless network for the purposes of detecting electrolyte accrual (internal or external) in insulated pipelines and vessels.

Conductivity measurements

The most common direct current (DC) technique for measuring conductivity, introduced by Wenner, makes use of a four-electrode measurement [19]. Four electrodes are arranged in a linear configuration and submerged in an electrolyte whose conductivity is to be measured. A known current is applied between the outer electrodes while the potential is measured between the inner electrodes with a high-impedance voltmeter. This approach minimizes the effect of polarization on the surfaces of the

outer (current-carrying) electrodes. If the inner electrodes are nominally identical from a material standpoint, their free corrosion potentials will cancel (once stabilized) and the potential difference registered will be entirely due to Ohmic potential gradients through the solution. The theoretical relationship between the inner-electrode potential and the electrolyte conductivity is dependent on the specific geometric configuration. For equally-spaced electrodes, flush mounted in a nonconductive base, the conductivity (σ) is given by:

$$\sigma = \frac{1}{2\pi Ra} \quad (1)$$

Where a is the center-to-center electrode spacing and R is the apparent resistance as determined by Ohm's Law ($R = V/I$) with V measured between the inner two electrodes when the current I is passed between the outer electrodes. The unit of conductivity is S/m where a Siemen (S) is equal to an Ohm^{-1} . Equation 1 assumes that the electrode spacing is large compared to the diameter of the electrodes. Tightly-spaced electrode configurations will deviate significantly from this limit case, but can be predicted with numerical simulations, or, established via calibration. A cell constant (K) can be used to capture the geometric and temperature effects of a particular probe configuration. In general:

$$\sigma = \frac{K}{R} \quad (2)$$

For the idealized Wenner formula in Equation 1 the cell constant is $1/(2\pi a)$. The units of the cell constant are m^{-1} . A calibration procedure would consist of measuring standard solutions in order to establish the relationship between K and the process variables (e.g. temperature).

An Alternating Current (AC) signal is sometimes used with two- and four-electrode configurations to further eliminate the effects of polarization [20]. At high frequencies, polarization effects disappear allowing only Ohmic potential gradients to be measured. If the AC signal does not have a DC offset, the outer electrodes would be expected to experience identical conditions over time and are less likely to drift and display hysteresis.

The deposition of solids is anticipated on conductivity probes operating in produced fluid streams. Accrual of solids and the deterioration of accuracy (electrode fouling) is expected to occur. Inductive (electrodeless) conductivity probes are typically favored in these types of environments [20]. Inductive conductivity probes and instrumentation tend to be more complicated and power-intensive than two- and four-electrode electrical probes.

The power requirements and complexity of measurement of a conductivity probe can be significantly reduced if continuity, rather than conductivity is to be measured. These measurements would be binary, with an established conductivity threshold based on the probe design and measurement procedure. Galvanic probe designs take advantage of the potential difference between dissimilar electrodes to greatly decrease the power requirements of the measurement system. This concept is utilized in passive electrochemical techniques such as Zero Resistance Ammetry (ZRA) and Electrochemical Noise (ECN) [21].

Commercial conductivity probes are typically concerned primarily with accuracy and sensitivity, and do not weigh power consumption heavily. In the case of locally-powered wireless networks of conductivity probes, power consumption and simplicity (cost) are the overriding parameters of interest. Accuracy and sensitivity are secondary.

Wireless Sensor Networks (WSN)

The concept behind a wireless sensor network (WSN) is to create a distributed network of wireless nodes that are able to communicate with each other (mesh network). These nodes exchange information, such as sensor readings, via radio signals using established wireless network protocols. By reducing the cost of each node higher nodal densities can be achieved, leading to increased network reliability. In

some WSNs data propagates throughout the entire network and can be accessed through any node. The speed of data propagation over the network depends on the distribution of nodes and the frequency of data transmission.

A natural application of WSNs is self-powered sensor nodes (or motes) for remote monitoring. Many such applications are described in the literature [22–29]. Low-power sensors, coupled with energy harvesting technology (e.g. PV solar, wind, etc.) provide low-maintenance measurement systems with relatively long lifecycles. Lund and Petersen previously developed and commercialized a solar-powered WSN (Zensor™)⁺ that has an estimated lifespan of 50 years [28,29]. These motes were specifically developed for very low-power applications where the change in the measurand is expected to be relatively slow. Each node uses a trickle charger connected to a small PV cell to charge a super capacitor. The mote remains in an ultra-low-power sleep mode, until enough charge has accrued and then wakes up, takes a measurement, and exchanges data with other nodes that are within range.

Lund and Petersen constructed a mesh network of 12 nodes covering approximately 5000m². Data propagated through the nodes at a rate of approximately 62 meters/hour [29]. On a larger network, (10 km x 10 km) would take 6.7 days for the data to fill the network. Operating at low power, the maximum range between nodes was estimated to be 100 meters. Larger internodal spacing is possible but would likely consume more power. Low-power WSNs are advantageous for remote monitoring applications where electrical infrastructure is non-existent or unreliable. The mesh configuration allows motes to be easily added, move, or removed without reprogramming the units. As long as every node is connected to the network, data will continue to propagate throughout the WSN.

Project Goal and Previous Work

The goal of this project is to develop and test a low-power, wireless sensor network of conductivity (or continuity) sensors that can be used to detect the presence of electrolyte (a requirement for corrosion) in pipelines and pressure vessels in the upstream oil and gas sector. The sensing elements will be designed for installation via industry-standard hydraulic access fittings. Since corrosion coupons currently occupy many existing access fittings, the design of the probes will allow for integration of a coupon holder. The present work is focused on the detection of internal electrolyte accrual, however, external accrual (i.e., CUI) is viewed as a natural extension of the technology.

The analysis and design a four-electrode conductivity probe and associated WSN electronics was described previously [30]. The results of the previous design work indicated that a pulsed DC technique provided the best balance of power consumption, accuracy, and sensitivity. The present work will focus on the testing and refinement of this design and the associated measurement technique.

Experimental Procedure

The experiments were performed using a 1.25-in-diameter prototype probe consisting of 3-mm-diameter graphite electrodes, spaced 5mm apart and mounted in non-conductive epoxy (see Figure 1). This prototype probe was used to conduct pulsed DC tests. Two power sources were used in the development of the measurement procedure (1) a Gamry 600 Potentiostat⁺ operating in galvanostatic mode and (2) a microcontroller. The former was used to establish operational limits of the probe, while the latter was used to determine practical limits of a realistic measurement system.

A circuit diagram of the measurement apparatus can be found in Figure 2. This apparatus was used to perform all of the pulsed DC microcontroller measurements. This microcontroller has a 10-bit Analog-to-Digital converter and a maximum sample rate of 125 kHz. In practice, potentiostatic control of the outer electrodes was utilized. A shunt resistor was used to determine the test current.

⁺ Trade name