ISA Transactions 55 (2015) 188–194

Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Development of self-powered wireless high temperature electrochemical sensor for in situ corrosion monitoring of coal-fired power plant

Naing Naing Aung [a], Edward Crowe [b], Xingbo Liu [a,*]

[a] Mechanical and Aerospace Engineering Department, West Virginia University, Morgantown, WV 26506, USA
[b] National Research Center for Coal and Energy, West Virginia University, Morgantown, WV 26506, USA

ARTICLE INFO

Article history:
Received 7 May 2014
Received in revised form
31 July 2014
Accepted 9 September 2014
Available online 3 October 2014
This paper was recommended for publication by He Peter

Keywords:
High temperature electrochemical sensor
In situ corrosion monitoring
Wireless communication
Thermoelectric generator

ABSTRACT

Reliable wireless high temperature electrochemical sensor technology is needed to provide in situ corrosion information for optimal predictive maintenance to ensure a high level of operational effectiveness under the harsh conditions present in coal-fired power generation systems. This research highlights the effectiveness of our novel high temperature electrochemical sensor for in situ coal ash hot corrosion monitoring in combination with the application of wireless communication and an energy harvesting thermoelectric generator (TEG). This self-powered sensor demonstrates the successful wireless transmission of both corrosion potential and corrosion current signals to a simulated control room environment.

1. Introduction

Increasing global energy demands, coupled with an ageing and inefficient fleet of power generation plants will require the deployment of next-generation ultra-supercritical (USC) coal-fired power plants [1,2]. One of the major hurdles in the development of USC power generation systems is managing coal ash hot corrosion which can lead to sudden catastrophic failure of USC boiler tubes [3–5]. An effective approach to improve reliability is to apply robust, in situ high temperature corrosion monitoring sensors to provide real time corrosion information so that the catastrophic failure can be prevented. Energy harvesting wireless sensor systems are more easily implemented with lower installation costs than traditional grid-powered sensors applied in harsh corrosion environments [6–8].

Combining the concept of energy harvesting and state-of-the-art wireless communication technology creates a nearly service-free data transmission system. In this case, a thermoelectric generator (TEG) is used as an energy harvester utilizing the heat transferred between the heat source and ambient air to generate electricity. TEGs are rugged, reliable, solid-state devices that convert heat directly into electricity [9–11]. They produce a constant power output for a given temperature difference between their hot and cold sides, can operate at elevated temperatures with supplementary cooling, and have proven to be reliable in various applications including harsh environments. A coal-fired boiler environment can provide the thermal energy necessary to produce sufficient power for robust, commercially available wireless instrumentation.

There are three major types of corrosion measurements that can be considered for use in high temperature corrosive environments: (1) the first type is a corrosion sensor where an alloy coupon would be incorporated into the *weight loss* test for a fixed period of time. It provides a quantitative corrosion rate, but the value only represents average corrosion over the fixed time period; (2) the second type is based on the *electrical resistance* of the sensor which measures the decrease in thickness of the sensor material as an increase in the sensor resistance. The data are very dependent on accurate temperature measurements and cannot distinguish localized corrosion; (3) a third type is one based on the measurement of *electrochemical signals*. These signals should be directly proportional to the corrosion rate and come in the form of linear polarization resistance (LPR), electrochemical impedance spectroscopy (EIS), and electrochemical noise analysis (ENA). Recently, it has been demonstrated that our novel high temperature electrochemical sensor can detect the hot corrosion

---

[*] Corresponding author. Tel.: +1 304 293 3339.
E-mail address: xingbo.liu@mail.wvu.edu (X. Liu).

http://dx.doi.org/10.1016/j.isatra.2014.09.003
0019-0578/

process and corrosion rate via different electrochemical techniques [12–15]. In the high temperature coal ash-covered corrosion conditions, the ohmic potential drop is an important consideration in the corrosion process [13,14]. Thus ohmic potential drops and nonuniform polarization current distribution problems can be effectively avoided using the ENA because it does not need an externally applied polarization as is the case with other electrochemical techniques such as the LPR and the EIS [16].

Electrochemical noise can be characterized in a three-electrode system in an electrolyte as fluctuations of electrochemical potential and current. Two of the electrodes are the identical working electrodes and the third one is a reference electrode. The potential (μV–mV range) is measured between the reference and the two working electrodes with a high impedance voltmeter, while the current (μA–mA range) between the two working electrodes is measured with a zero resistance ammeter. Typically, the events take place at frequencies less than 1 Hz [17]. The magnitude, duration and frequency of the fluctuations can be used to determine the prevailing corrosion mechanism. The ENA can differentiate between general or localized forms of corrosion and provides estimates of corrosion rates. Each type of localized corrosion process will have a characteristic signature in the noise signal. This signature can be used to identify the type and severity of corrosion that is occurring. The potential and current signals from ENA can directly correlate with coal ash hot corrosion processes and reaction kinetics [13–15]. In this case, the inclusion of a wireless communication system can manage the data transmission requirements of the complex electrochemical signals generated by the high temperature electrochemical sensor.

In analogous research, sensors have been developed for monitoring the corrosion of reinforcement in concrete structures [18–20]. However, the development of high temperature electrochemical sensors is still a challenging issue. The main objective of the research is to develop new sensing technology and instrumentation systems capable of surviving harsh industrial environments. In this case, a proof of concept study of a self-powered wireless high temperature electrochemical sensor will be described.

2. Experimental setups

2.1. Sensing strategy of self-powered wireless high temperature electrochemical sensor

The key innovation of the sensing strategy is the combination of the high temperature corrosion sensor with electrochemical noise analysis technology and the application of a self-powered wireless sensor network. The conceptual design of the sensing system is shown in Fig. 1. The design includes four individual modules: (1) high temperature electrochemical sensor; (2) potential/current amplification system; (3) wireless communication system; and (4) thermoelectric generator for energy harvesting.

2.2. High temperature electrochemical sensor

The sensor was based on a four-electrode system which includes two identical working electrodes (WE1 and WE2), one reference electrode (RE) and one counter electrode (CE). The schematic design of the sensor is shown in Fig. 2. It was specially designed to utilize the response of ENA, EIS and LPR to study the corrosion behavior. However, for real time wireless transmission of electrochemical signals ENA is the most suitable technique to detect and analyze the corrosion process as well as corrosion rates.

The monitoring principle of an electrochemical noise based high temperature electrochemical sensor is the direct transmission of thermodynamic and kinetic responses represented by electrochemical hot corrosion reactions. Different potential levels are imposed due to the activity of corrosion and the current flow is proportional to the extent of corrosion. Time-dependent fluctuations of potential noise signal can be recorded from the WE1 and RE while the WE1 and WE2 transmit the current noise signal. The potential/current noise signals from the sensor were conditioned by a JFET operational amplifier interface for transmission by the wireless communication system.

The working electrodes were fabricated using the same materials as the structure being monitored. One of the unique aspects of the sensor is the inclusion of a solid state Ag/Ag^+ reference electrode to measure the potential between this reference electrode and the working electrode that is sensitive to specific ionic species under high temperature conditions. The reference electrode contained 10 mol% Ag_2SO_4 in the 90 mol% Na_2SO_4 molten salt. The Ag wire was inserted into the fused-quartz (GE 214) tube to allow the Ag wire to be immersed in the molten salt. The top of the reference electrode was sealed to prevent an evaporation of the molten salt at high temperatures. Its stability allowed the sensor to have a good reference point and better isolate the electrochemical corrosion information from other noise in the environment. A platinum wire was used as a counter electrode.

2.3. Potential/current amplification system

To improve the interface between the corrosion sensor and the commercial wireless system two JFET operational amplifiers were utilized to serve as high impedance buffers (Fig. 3). Fig. 3(a) is a screen shot of the integrated interface circuitry designed and simulated in National Instrument's Multisim™ 13.0. The three circuit elements consist of a “rail splitter” which converts the 24 VDC supplied by the thermoelectric generator and DC to DC converter to a dual rail ± 12 VDC supply with virtual ground; a JFET unity gain amplifier to serve as a high impedance input for the mV signal between the working electrode and reference electrode; and a high gain (3×10^5) JFET amplifier to convert the μA noise signal between the WE1 and WE2 to a low potential signal that can be transmitted via the wireless communication system. This interface has been built and tested to verify functionality when powered by the thermoelectric generator.

2.4. Wireless communication system

The wireless sensor network can demonstrate the capability of a state-of-the-art commercial wireless system to manage the data transmission requirements of the potential and current noise signals generated by the high temperature electrochemical sensor system. The hardware chosen was a 1 W transmitter with frequency-hopping, spread spectrum technology in the 902–928 MHz ISM band. This was chosen to minimize signal degradation that may be accentuated with higher frequency carrier signals. The signal converter will convert the mV output of the JFET amplifiers to a 4–20 mA signal to be transmitted wirelessly to a remote receiver. The transmitter configuration consists of a DC to DC converter with a 12–24 VDC input and 24 VDC output and a configurable signal converter mounted to a rail as shown in Fig. 4. A thermoelectric generator serves as the power source with a variable output voltage as the input to the DC-DC converter with the regulated 24 VDC output supplying the transmitters and JFET amplifiers.

2.5. Thermoelectric generator for energy harvesting

Thermoelectric generators utilize the principle of the Seebeck effect to convert a temperature difference across a semiconductor module to an electric voltage. Although typical efficiencies are only in the range of 5–8%, it is a viable method for energy harvesting to