Development of Self-Powered Wireless-Ready High Temperature Electrochemical Sensor For In-Situ Corrosion Monitoring of Coal-Fired Boiler Tubes

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Project Objectives

- To develop a self-powered wireless high temperature electrochemical sensor for in situ monitoring hot corrosion under the harsh conditions present in coal-based power generation system.
- To develop thermal-electric based energy harvesting and telecommunication devices for the self-powered wireless ready sensor system.
Key Innovations of the Sensing Strategy

Electrochemical Noise Based High Temperature Electrochemical Sensor Technology

Wireless Communication Technology

Energy Harvesting Technology
Thermoelectric Generator (TEG)
Conceptual Design of the Sensing System

1. High Temperature Electrochemical Sensor
2. Potential/Current Amplification System
3. Signal Converter
4. TEG System
   - Transmitter
   - Data Logger
   - Signal Receiver
Our Developed High Temperature Corrosion Sensor

Working electrodes 1, 2 & 3

Counter electrode

Reference electrode

WE-1
WE-2
WE-3
CE
RE

Current noise

Potential noise

Potentiodynamic Polarization

EIS

WE-1
WE-2
WE-1
RE
CE
WE-1
WE-2
Sensibility Test of Self-Powered Wireless-Ready High Temperature Electrochemical Sensor Before Wireless Transmission
# Experimental Conditions for Sensibility and Reliability Tests

<table>
<thead>
<tr>
<th>Corrosion condition</th>
<th></th>
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</thead>
<tbody>
<tr>
<td><strong>Materials</strong></td>
<td>IN 740-1</td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td>650-850°C</td>
</tr>
<tr>
<td><strong>The Flue Gas Composition</strong></td>
<td>With/without SO$_2$ 15 CO$_2$ + 4 O$_2$ + 80 N$_2$ + 1 SO$_2$</td>
</tr>
<tr>
<td><strong>Coal ash thickness</strong></td>
<td>Thin film 89 % Ash +10% Alkali +1% NaCl</td>
</tr>
<tr>
<td><strong>Exposure time</strong></td>
<td>60 days</td>
</tr>
</tbody>
</table>
THREE Different Stages of Coal Ash Hot Corrosion Process

Oxidation Stage

Sulfidation Stage

Oxidation in Cr,Ni-rich regions

External Sulfidation in Cr,Ni-rich regions

Internal Sulfidation in Ni,Cr-rich regions
Oxygen and Sulfur Diffusion During Oxidation & Sulfidation Stages

- **Oxidation** in Cr,Ni-rich regions
- **External Sulfidation** in Cr,Ni-rich regions
- **Internal Sulfidation** in Ni,Cr-rich regions
Reproducibility of Potential and Current Signals During Oxidation and Sulfidation

IN 740-1 alloy + 850 °C + Thin coal ash + without /with SO₂
FIVE Typical Noise Signals Measured in the Coal Ash Hot Corrosion Process

**Electrochemical Potential Noise Signals**

- The noise signature of a gradual potential continuously changing in the negative region (*Noise Signature I*) corresponded with the Oxidation Stage.
- The noise signature of quick potential continuously approaching more positive values (*Noise Signature II*) correlated to the External Sulfidation Stage.
- The noise signature of positive potential fluctuating randomly in a narrow range (*Noise Signature III*) corresponded with the Internal Sulfidation Stage.

**Electrochemical Current Noise Signals**

- Signature of current fluctuating with no sudden spike correlated to the Low Extent of Oxidation/Sulfidation (*Noise Signature IV*).
- The noise pattern of sudden change in current values followed by slow or no recovery corresponded with the Accelerated Oxidation/Sulfidation (*Noise Signature V*). These signatures can be seen clearly at 750 °C, in the flue gas without SO₂ as well as deep coal ash.
Corrosion Potential Range in Different Coal Ash Hot Corrosion Conditions

- Sulfidation at 700 °C with SO₂ in thin coal ash
- Sulfidation at 800 °C with SO₂ in thin coal ash
- Sulfidation at 750 °C with SO₂ in thin coal ash
- Sulfidation at 800 °C with SO₂ in deep coal ash
- Oxidation at 750 °C without SO₂ in thin coal ash
Corrosion Current Range in Different Coal Ash Hot Corrosion Conditions

Sulfidation at 750 °C with SO₂ in thin coal ash
Sulfidation at 800 °C with SO₂ in deep coal ash
Sulfidation at 700 °C with SO₂ in thin coal ash
Sulfidation at 800 °C with SO₂ in thin coal ash
Oxidation at 750 °C without SO₂ in thin coal ash

\[ i (\mu A \text{cm}^{-2}) \]

Time (ks)
New Version of Faraday’s Law Expression for Calculation of Hot Corrosion Kinetics

Corrosion Rate, \( R = \frac{KM}{n\rho} \ i_{max} \)

- \( K \) = Constant for converting units
- \( M \) = Atomic mass
- \( n \) = Number of electrons freed by the corrosion reaction
- \( \rho \) = Density

Corrosion Depth, \( D = K \times R \times \text{period} \)

where the period is normally 24 h and the corrosion rate is assumed to be constant
Evaluation of Corrosion Rates

- Accelerated internal sulfidation at 750 °C
- Internal sulfidation at 800 °C
- External sulfidation at 700 °C
- Oxidation in the flue gas without SO₂
- Accelerated internal sulfidation in deep coal ash

Corrosion rate (mm y⁻¹)

Exposure time (h)
Evaluation of Metal Losses

Accreled internal sulfidation at 750 °C
Oxidation in the flue gas without SO₂
Accreled internal sulfidation in deep coal ash
Internal sulfidation at 800 °C
External sulfidation at 700 °C

Accumulated mass loss (g)

Exposure time (h)
Sensibility Test of Self-Powered Wireless-Ready High Temperature Electrochemical Sensor After Wireless Transmission
Experimental Set up for Self-Powered Wireless Sensing

Thermoelectric Generator (TEG)

Potential Signal

Potential Amplification System

Current Signal

Current Amplification System

Transmitters
Wireless Potential Signal from Oxidation & Sulfidation Stages

IN 740-1 alloy + Thin coal ash + with/without SO₂
Wireless Current Signals from Oxidation & Sulfidation Stages

IN 740-1 alloy + Thin coal ash + with/without SO₂
Potential Signal Transmission For 30 Days

IN 740-1 alloy + Thin coal ash + with/without SO₂
Current Signal Transmission For 30 Days

IN 740-1 alloy + Thin coal ash + with/without SO$_2$
Concurrent Transmission of Potential and Current Signals
Oxidation at Different Temperatures

IN 740-1 alloy + Thin coal ash + without SO₂

Graph showing the change in electrochemical potential ($E$) and current density ($I$) over time ($t$) during oxidation at different temperatures (750°C, 850°C, 650°C). The graph illustrates the behavior of IN 740-1 alloy in the presence of thin coal ash without SO₂.
Concurrent Transmission of Potential and Current Signals
Oxidation & Sulfidation at 750 °C

IN 740-1 alloy + Thin coal ash + with/without SO₂
Testing Sensor in Industrial USC Boiler Setting
(Western Research Institute, Laramie WY)
Sensor Setting inside Coal Combustion System
Sensor Setting inside Coal Combustion System
Potential/Current Signals Measured from Corrosion in the Coal Combustion System
Project Milestones

June 2011 to Dec 2013
- To develop the high temperature electrochemical sensor
- To demonstrate sensitivity and long term reliability of the high temperature electrochemical sensor
- To develop TEG and wireless communication system

January to June 2014
- To demonstrate sensitivity of the self-powered wireless high temperature electrochemical sensor

June to December 2014
- To demonstrate long term reliability of the self-powered wireless high temperature electrochemical sensor

January to June 2015
- To develop data/knowledge-base on coal ash composition effect on EN/corrosion signals
Publications


Conclusions

- A novel self-powered wireless high temperature electrochemical sensor technology has been developed to provide in situ corrosion information to assist in coal-fired power generation systems.

- Electrochemical potential and current noise signals from a simulated coal ash hot corrosion process were wirelessly transmitted and recorded for approximately two months to evaluate the sensibility of the sensor.

- The high sensibility and the reproducible lab-scale experimental results demonstrate the reliability of the sensor for long-term stability in commercial coal-fired boiler applications.
Localized Corrosion Identification

Localization Indices of Oxidation and Sulfidation at 750 °C

Localization Indices of Sulfidation at Different Temperatures
Future Works

- To expand the functionality of the high temperature in-situ electrochemical sensor system with a design that can identify the location localized corrosion

- To investigate the underlying mechanism of the observed electrochemical corrosion noise
Thank You