Monitoring Erosion-Corrosion in Carbon Steel Elbow Using Acoustic Emission Technique

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Abstract
The most crucial factor in pipeline operating system is the control of the pipe’s erosion-corrosion, especially in weak parts such as elbows. Hence, online monitoring for erosion-corrosion in pipeline is extremely important for early detection of any abnormal phenomena that may lead to catastrophic accidents. Pre-diagnosis enhances the safety and integrity of the whole pipeline systems. One of the several methods that can be applied to detect the erosion-corrosion in pipeline is by using the detection of the acoustic emission (AE) during the operation of the pipeline. An application of this method is carried out in the present laboratory work. To examine the rate of erosion-corrosion in 2” carbon steel 90 degree elbow within plastic pipeline system running with seawater at different velocities. The results show great ability and sensitivity of AE technique in early erosion-corrosion detection for elbows during operation.

Keywords: Signal processing, structural health monitoring, erosion-corrosion, acoustic emission, laminar flow, turbulent flow.

1. Introduction

The arteries and veins of our modern civilization are the pipelines. Pipelines are commonly spread in most oil and gas industrial systems for transmission fluids or for cooling processes for either in shore or offshore applications. Since a pipeline networks can be classified as a safety critical system, continuous monitoring and diagnosis of pipelines have a great importance in order to detect early the abnormal behaviour that may lead to catastrophic accidents of environmental impact (e.g. erosion-corrosion in pipeline systems). In addition, a fault can be costly in terms of production loss. There are several direct and indirect methods that can be applied to detect the erosion-corrosion in pipeline [1-6].

One of the indirect methods is by using the detection of the acoustic emission (AE) during the operation of the pipeline. AE has the highest accuracy in quantified damages for intermediate and relative high corrosion rates. By comparison with other techniques, the sensitivity of the AE technique is higher than other non-destructive testing methods like dye penetrant, magnetic interference or ultrasonic testing [1, 7]. Since the early detection of erosion-corrosion enhances the overall system dependability and safety, AE assessment can be used as the basis for continuous plant monitoring, increasing structural safety and reducing shutdown costs for inspection [2].

In the present paper, a series of laboratory experiments are carried out to monitor the behaviour of real source (erosion-corrosion) in a carbon steel elbow using AE method. The elbows are connected to plastic pipeline system filled with seawater running at different flow rates (i.e. laminar and turbulent). AE signal is analysed in frequency and time domains using commercial software.
2. Monitoring erosion-corrosion

Erosion-corrosion is the general term encompassing a spectrum of mechanisms from accelerated corrosion to a purely mechanical damage, which causes high rates of material loss in industries [3-5]. Another definition it is the acceleration or increase in rate of deterioration or attack on a metal because of the relative movement between a corrosive fluid and the metal surface [6]. Generally this movement is quite rapid, and mechanical wear effects or abrasion are involved. Erosion results in removal of surface layer gradually in form of small chopping [5]. Erosion-corrosion is characterized in appearance by grooves, gullies, waves, rounded holes and usually exhibits a directional pattern [6].

Acoustic Emission (AE) is stress waves produced by sudden movement in stressed materials [7-12]. The traditional emission sources are defect-related deformation processes such as crack growth and plastic deformation [7]. The AE propagation from the source, throughout the structure can be listened and that technique is used worldwide for detecting and locating defects as they occur, across the entire monitored area, providing early warning of failure, in a timely and cost effective manner [8]. For example, Yuyama and Nishida [9] have presented the AE techniques in evaluation of corrosion damages in buried pipes. They conducted many tests in laboratory and field. Machijima et al. [10] used AE for online monitoring, to improve a great ability in detecting corrosion under insulation of piping during operation. They have used the AE hits to monitor the corrosion progress. Furthermore, Kim et al. [11] used AE for detecting and monitoring of crevice corrosion with AE signals. During crevice corrosion, AE signals showed higher average and maximum values. Also Phillip and Stephen [12] have used the AE technique for detecting corrosion under the insulation of a sulphur tank, in which AE hits and amplitude show the ability of AE technique in monitoring corrosion.

3. Experimental apparatus & procedures

Experiments were carried out on a 2" carbon steel 90 degree elbow LR with 50.8 mm internal diameter and 2.8 mm wall thickness. For a smooth and clean inner surface of the elbow before starting the test, see Figure 1. In order to know the iron weight loss from the elbow during operation in a pipeline system in the lab, the components of the whole system must be made from plastic apart from the carbon steel elbow. In Figure 2, the model is made for the plastic operating system to be similar to any operating system in all fields. A high resistance polypropylene pipes and fittings (e.g. elbow, valves, etc.) were selected as the main parts of the system because of their advantages for: long duration, better flexibility, high resistance to salt, chemical, pressure and heat. Also plastic water tank and a stainless steel bump, with high corrosion resistance.

Figure 1. Internal surface of new elbow
As mentioned before, the aim of this research work is to monitor erosion-corrosion at laminar and turbulent flow. Reynolds number has been calculated for laminar flow (i.e. Re < 2300) and for turbulent flow (i.e. Re > 2300) [13]. Reynolds number is given by the following expression:

$$Re = \frac{\rho V d}{\mu}$$ ......................................................... (1)

where $\rho$ is 1025 (kg/m$^3$), $\mu$ is 0.0011 (kg/ms), and $d$ is 0.053 (m) 
the flow velocity (m/s)

$$V = \frac{q}{Area}$$ ................................................................. (2)

where $Area$ is 0.00221 (m$^2$), and $q$ is the volume Flow rate (m$^3$/s)

The erosion-corrosion analysis in this experiment is carried out for the determination of its rate in the elbow by changing flow rate every 1 hour. A sample of the outlet water was taken in a cleaned test tube washed with distilled water every 20 minutes from the elbow and at the same time acquiring an AE signals for 1 minute duration. Three velocities for the laminar state are considered (Re 582, 1176 and 2148), and four velocities for the turbulent state (Re 7878, 13107, 19296 and 25922).

Hach DR/2010 Spectrophotometer is a microprocessor-controlled, single-beam instrument for colorimetric testing in the laboratory or the field. This is used to measure the quantity of iron (loss from the elbow) in each sample of seawater. Also ferrover iron reagent was used to determine the quantity of iron in seawater.

The loss of weight was estimated from the quantity of iron loss from the carbon steel elbow. Erosion-corrosion rate is given by the following expression:

$$\text{Erosion-corrosion rate} = \frac{LW}{(A \times T)}$$ ................................................. (3)

where $LW$ = Iron loss weight (mg)
$A$ = Elbow area (m$^2$)
$T$ = Time (min)
Commercials AE acquisition system and software are used. The AE system is consisting of an array of two sensors and a Physical Acoustics Pocket (AE) system which is computerized hand-held instrument for AE testing. Due to its portable nature and full AE features and functions capabilities, this system can be used in any remote applications and evaluation of AE. It performs traditional AE feature extraction based on AE signal processing, as well as advanced waveform based acquisition and processing. The Pocket AE has a built-in, internal preamplifier and also has the capability for powering a low power line of external preamplifiers and/or integral preamplifier sensors, which give the ability to select between the use of the internal and external preamplifier via software.

The Pocket AE is attached with Physical Acoustics R15a (the “a” stands for Alpha series of sensors) sensors. These sensors have a built in amplifiers and a fairly flat frequency response but with two bands of relatively high sensitivity at around 50kHz and 200kHz and they have an operating temperature from -65 C to 177 C. The sensors are 19 mm diameter, 22 mm height and 34 gm weight and held onto the elbow surface. In order to obtain good coupling of the AE, the surface was kept smooth and clean and silicone grease was used as couplant to fill any gaps caused by surface roughness and eliminate air gaps which might otherwise impair AE transmission. All experiments were analysed by computer using commercial data acquisition and signal processing software. The software package used in this paper was Noesis for Pocket AE.

4. Results and discussion

Analysis techniques are developed here to extract significant features of erosion-corrosion rate and of the AE signal associated with real sources, based mostly on techniques using hits, energy, frequency, time, counts and amplitude.

4.1 Erosion-corrosion analysis

The erosion-corrosion rate was calculated for seven different velocities with 20 minutes increment as presented in Table 1. Figure 3 (a) shows a linear relationship between the erosion-corrosion rate and the velocity for the flow for the laminar case during 1 hour for each Re. Figure 3 (b) shows the same relation for the turbulent flow case. From the observation of the trends it is shown that at all time intervals the increase of erosion-corrosion rate is very high due to the change in velocity of the flow for the laminar or turbulent cases.
4.2 AE signals analysis

For monitoring erosion-corrosion with association of acoustic emission, an AE signal was taken at each sample. By analyzing these signals many parameters such as Hits, Amplitude, counts, energy, frequency and time, can all show how effective is the AE technique for monitoring erosion-corrosion in elbows during operation time at different velocities of flow. Each signal was double checked by acquiring the signal two times insuring that the two signals were correct. For analyzing the AE signal and illustrating the difference between flow velocities and its relation to the erosion-corrosion rate, a comparison between AE signals are built on choosing a random signal from each flow rate and the first signal which was taken at the start of the elbow operation (S1). These main AE signals are shown in Table 1.

Table 1. Erosion-corrosion rate calculations and AE signals

<table>
<thead>
<tr>
<th>Item</th>
<th>Flow Type</th>
<th>Re</th>
<th>Time(min.)</th>
<th>Erosion-corrosion rate in seawater (mg/m²min)</th>
<th>AE signals</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Laminar</td>
<td>582.68</td>
<td>20</td>
<td>0.022</td>
<td>S2</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td>60</td>
<td>0.027</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Laminar</td>
<td>1176.63</td>
<td>20</td>
<td>0.036</td>
<td>S3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40</td>
<td>0.040</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>60</td>
<td>0.044</td>
<td></td>
</tr>
<tr>
<td>3</td>
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<td>2148.72</td>
<td>20</td>
<td>0.053</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40</td>
<td>0.052</td>
<td>S4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>60</td>
<td>0.054</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Turbulent</td>
<td>7878.79</td>
<td>20</td>
<td>0.093</td>
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<td></td>
<td></td>
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<td>40</td>
<td>0.090</td>
<td></td>
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<td></td>
<td></td>
<td>60</td>
<td>0.095</td>
<td>S5</td>
</tr>
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<td>5</td>
<td>Turbulent</td>
<td>13107.75</td>
<td>20</td>
<td>0.118</td>
<td>S6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40</td>
<td>0.121</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>60</td>
<td>0.122</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Turbulent</td>
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<td>20</td>
<td>0.129</td>
<td></td>
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<tr>
<td></td>
<td></td>
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<td>S7</td>
</tr>
<tr>
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<td></td>
<td>60</td>
<td>0.135</td>
<td></td>
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<tr>
<td>7</td>
<td>Turbulent</td>
<td>25922.2</td>
<td>20</td>
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<td></td>
<td></td>
<td>60</td>
<td>0.152</td>
<td>S8</td>
</tr>
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</table>
4.2.1 AE Hits analyses

Figure 4 (a) shows the carbon steel elbow from inside after seven hours of operation with both laminar and turbulent flows and in Figure 4 (b), the same elbow but after only three hours of operation with laminar flow. The difference between the two photos in Figures 4 (a, b) can be observed, as the shape and numbers of erosion-corrosion in the elbow increase by increasing the flow velocity. The number of hits is related to the flow velocity, see Figure 5. AE can be the result of the friction force between seawater and the wall of the elbow. When the rate of iron loss from the elbow increases, the number of hits increases. For example, in laminar states, Figures 5 (a, b), the number of cumulative hits increases from 6 hits at the first minute of operation at Re 582 and increased to 64 hits after 20 minutes. For laminar flow of Re 1176, cumulative hits increased to 440 hits. This value rose to 460 hits at Re 2148. By increasing the flow velocity reaching the turbulent flow case, the number of cumulative AE hits decreases in comparison to the cumulative hits for the laminar flow, see Figures 5 (c, d). In Figure 5 (c), the cumulative hits is about 95 hit at Re of 7878 and it decreases to 75 hit at Re 13107. The cumulative hits increases to 97 hit at Re 19296 and at Re 25922, the cumulative hits reaches 122 hit as shown in Figure 5 (d).

![Figure 4. Inside elbow after operation](image)

(a) Seven hours of operation (Laminar & turbulent flow)  
(b) Three hours of operation (Laminar flow)

4.2.2 AE Amplitude analyses

The amplitude of the AE signal is also seen to be practically capable to describe the process of erosion corrosion. The AE activity and propagation, plays the most important role in characterizing the real phenomena of the process with variable velocities. It is clearly observed that when the velocities increase, the amplitude is associated with a wide range and the AE activity starts very poor at the beginning. The amplitude range is 65 dB with a low AE activity with hits intensity of 4 hit at Re 582 after 20 minutes. In Figure 6 (a), AE activity increases as the range of amplitude increases from 61 dB to 65 dB with hits increasing to 11 hit at Re 1176. In Figure 6 (b), the amplitude range increases from 61 dB to 67 dB with the same hits intensity at Re 2148.
When the velocity of the flow increases to Re 7878 (turbulent flow), the intensity of hits decreases to 3 hits at amplitude range 68 dB to 70 dB with a very low AE activities, Figure 6 (c). Also, Figure 6 (d), the AE activity starts to increase again with increasing number of hits at range of amplitude 69 dB to 73 dB at Re 19296. At Re 25922, the intensity of hits increases and becomes 4 hits at the same amplitude. This shows that the AE activity decreases due to turbulence of the flow and starts to increase by increasing the flow velocity. However, these results clearly show 6 to 8 dB higher amplitude in the turbulent flow conditions, indicative of more aggressive erosion state.
4.2.3 AE Energy analyses

The AE energy analysis was applied to the AE results in order to study the amount of energy at each velocity, and the relation to hit intensity (the number of hits of the same energy) to identify the rate of erosion-corrosion. From Figure 7 (a), Re 1176, the AE energy is concentrated in the range of 5000 v².s with 8 hits intensity. At Re 2148, the concentration of energy increased to 10000 v².s with 9 hit intensity, as shown in Figure 7 (b). It begins with a low energy that was less than 1000 v².s and 1 hit at Re 582 after the first minute of operation then it increases to 2 hits after 20 minutes with a very low AE energy activity. It is shown that at laminar flow, the AE energy is directly proportional to the velocity of the flow and so is the erosion-corrosion rate. From Figure 7 (c, d), it seems that the flow becomes turbulent as the number of hits decreases to 3 hits and stay steady state at Re 13107, 19296 and 25922, which it starts with 2 hits at Re 7878 with a very low AE energy activity. Generally speaking, energy activity increases by increasing the flow velocity. This can be seen in some hits reaching a very high level of AE energy reaching saturation at 65000 v²s. It can be summarized that at turbulent flow of seawater, the AE energy reaches a high level with a linear shape with a very poor concentration of energy and very low number of hits intensity. Thus, the energy level reaching the saturation or higher indicates active erosion-corrosion, while the hit intensity data is a poor indicator of erosion-corrosion.

4.2.4 Counts and Amplitude analyses

From the previous results it could be clearly observed that AE counts were increased by increasing the flow velocity. In Figure 8 (a), laminar flow at Re 1176, the number of counts is 1331 and the maximum amplitude is 65 dB which starts at Re 582 with 700 counts and ends at Re of 2148 with 1350 counts at 67 dB. Thereafter, the number of counts increases when flow reaches turbulent state that the number of counts increases to 1400 at 70 dB and Re of 7878, as shown in Figure 8 (b). Hence, as the velocity increases, the number of counts and amplitude increase, until reaches 1675 counts at amplitude 73 dB and Re 25922. By observing the laminar flow, it is found that all of the forms for counts and amplitude have the same shape (uniform shape).
4.2.5 Frequency analyses

The frequency analysis was used to determine the frequency range of the erosion-corrosion. A typical AE signal for the hit with the highest amplitude was recorded. Frequency responses were filtered by a high pass filter (Chebyshev I) applied at 50 kHz to have good identification of the required signal. The frequency range at laminar flow is between 60 to 300 kHz. Frequencies of laminar flow have a similar shape of wave with different peaks and activity, and it is increased with increasing the velocity of the flow and the erosion-corrosion rate, as shown in Figure 9 (a, b). The mostly high frequency band is around 110 kHz. In Figure 9 (c), the shape of the frequency spectrum is totally changed because the flow has become turbulent. The effective range of frequency for turbulent flow is around 60 to 350 kHz, and the highest peak is about 130 kHz.
4.3 AE and erosion-corrosion rate comparison

The analysis is to be completed by a comparison to show the ability of AE in monitoring erosion-corrosion. Figure 10 (a), it can be seen that for laminar flow the rate of erosion-corrosion is directly proportional with the number of hits when the velocity increases. For turbulent flow, Figure 10 (b), the same linear relationship holds between hits, erosion-corrosion rate and Re.

Figure 9. AE power spectrum for the hit for seawater

(a) S1
(b) S2
(c) S6

(a) For laminar flow
5. Conclusions

This research is aimed at investigating the monitoring of erosion-corrosion by AE technique, and the following conclusions are drawn:

- Erosion-corrosion propagation leads to an increase of AE activity and to the emission of signals with high value of hits, number of counts, amplitude, frequency and energy.
- The range of the amplitude for erosion-corrosion for carbon steel elbow in a fully operating system is between 60 dB to 71 dB.
- The most effective range of amplitude for erosion-corrosion in case of laminar flow is between 61 dB to 65 dB, and for turbulent from 68 dB up to 72 dB.
- From AE signals, it is possible to identify whether the type of the flow is laminar or turbulent, which can be done by the form of the AE energy, which for turbulent flow reaches a very high level of AE energy above the saturation level of 65000 V².s with low activity. On the other hand for laminar flow it shows a high AE activity and propagation at lower AE energy level.
- Also from the correlation between counts and amplitude, a laminar flow can be identified from turbulent flow without the need to know the velocity of the flow by checking the form of the signal as it has a uniform shape unlike turbulent flow.
- The frequency range of erosion-corrosion in seawater 60-350 kHz and the maximum peak is 110 kHz for laminar flow and 130 kHz for turbulent one.
- Rate of erosion-corrosion is directly proportional to hits as the velocity increases.
- Generally, AE method is a promising technique to monitor the erosion-corrosion process in carbon steel pipelines.

References


