Accelerated corrosion of pipeline steel and reduced cathodic protection effectiveness under direct current interference

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HIGHLIGHTS

- Measured the potential of pipeline steel under direct current (DC) densities.
- Quantified the accelerated corrosion rate of the steel under DC interference.
- Determined the shift of cathodic protection potential in the presence of DC.
- Determined the electrolyte alkalinisation caused by DC stray current.

ARTICLE INFO

ABSTRACT

In this work, corrosion of an X52 pipeline steel at various direct current (DC) densities was investigated in an extracted soil solution by potential and pH measurements, weight-loss testing and optical microscopy. It was found that the DC stray current could polarize, either anodically or cathodically, the steel at the anodic and cathodic zones, respectively, resulting in accelerated corrosion of the steel and the cathodic reduction of dissolved oxygen. The CP potential was not maintained at the applied value under the DC interference, and was shifted to positive and negative directions in the anodic and cathodic zones, respectively. The pipeline suffered from both anodic and cathodic DC interferences. The steel in the anodic zone cannot be protected, at least not fully protected, by the CP from corrosion. The solution alkalization in the cathodic zone would be further enhanced due to the combined effect of DC and CP on cathodic reaction. The implications of the DC interference on pipeline integrity were discussed.

1. Introduction

Stray current refers to the electric current flowing through conductive paths other than the intended ones [1]. Corrosion of metals can be caused by the stray current interference [2]. In the 1960s, Schwalm and Sandor [3] determined that the stray current, including both alternating current (AC) and direct current (DC) ones, was able to accelerate corrosion of buried pipelines. The stray current can be categorized into dynamic or static ones based on the fact whether the amplitude and direction of the current change over time [4,5]. Generally, the static stray current interference that a pipeline is subject to is generated by outside current sources, such as high-voltage AC or DC powerlines, DC rectifiers, etc. The dynamic current interference is mostly from the orbital transport system, i.e., city transit systems. When collocated with the stray current sources, the pipeline would suffer from accelerated corrosion, resulting in the so-called AC or DC corrosion [6–15].

The DC corrosion of buried pipelines is similar to classic corrosion mechanism, i.e., current flows from anode to cathode through the soil electrolyte by ionic conductivity and from cathode to anode through the pipeline by electrons [16]. At the anode, the pipe steel oxidizes; and at the cathode, hydrogen evolution or the oxygen reduction occurs. Thus, steel corrosion occurs at the anode, with no corrosion attack at the cathode. The corrosion kinetics obeys Faraday's law, i.e., 1 ampere of DC discharge from a pipeline may consume 10 kg of steel within one year [17]. Generally, the DC can cause more serious corrosion than AC on pipeline steels. McIntosh [18] demonstrated that the corrosion of steels under AC interference of 60 Hz is about 1% of that induced by an equivalent amount of DC. Moreover, the DC corrosion is localized in nature. Corrosion reaction occurs at the anode where the pipe steel is exposed to soil due to local breakage of external coatings, which can result in dramatic consequences on pipelines [19,20].

Different from AC corrosion, there have been limited investigations on DC corrosion of pipelines, including parametric effects and the mutual interference of DC with cathodic protection (CP) [21–24]. For example, the CP criterion recommended by NACE International to protect underground steel structures from corrosion attack is a cathodic potential of −850 mV vs. copper sulfate electrode (CSE) [25]. However, the presence of DC interference can decrease the effectiveness of CP by shifting the applied CP potential from the designed value. There has been so far rare understanding of the quantitative relationship between DC current density and the CP potential shift.

The DC corrosion of buried pipelines has attracted increasing attention recently along with the design and construction of high-voltage DC (HVDC) power lines, which are usually located in energy corridors where oil/gas pipelines are buried. This is particularly true in Alberta, Canada, where the proposed HVDC lines are adjacent to energy pipelines over a long distance. Obviously, investigations of DC corrosion of pipelines not only improve our understanding to this important phenomenon, but also meet immediate industry and society needs for safe and reliable design of energy infrastructure.

In this work, corrosion of an X52 pipeline steel at various DC current densities was investigated in an extracted soil solution by potential and pH measurements, weight-loss testing and optical microscopy. The effect of DC current density on both anodic and cathodic reactions was determined. The shift of CP potential under DC interference was measured. The mechanistic aspects about the accelerated pipeline corrosion and reduced CP effectiveness in the presence of DC interference were analyzed. The implications of the DC interference on pipeline integrity were discussed.

2. Experimental

2.1. Specimen and solution

Specimens used in this work were cut from an X52 steel pipe, with a chemical composition (wt.%): 0.24 C, 1.4 Mn, 0.45 Si, 0.025 P, 0.015 S, 0.10 V, 0.05 Nb, 0.04 Ti and Fe balance. The steel coupons were machined into 10 mm × 10 mm, and were sealed with epoxy, leaving an area of 100 mm^2. The specimen preparation was controlled carefully to ensure that there was no bubble and crevice at the epoxy/steel interface. All specimens were ground with 240, 400, 600, 800, and 1000 grit emery papers, followed by cleaning in distilled water and methanol, and drying in air.

To simulate the Regina clay soil (Saskatoon, Canada) where the pipeline was buried, an extracted soil solution was used in this work, which contained 0.0755 g/L NaHCO$_3$, 0.0092 g/L NaCl, 0.0014 g/L NaNO$_3$, 0.0773 g/L Na$_2$SO$_4$, 0.0619 g/L K$_2$SO$_4$, 1.116 g/L CaSO$_4$·2H$_2$O and 0.662 g/L MgSO$_4$·7H$_2$O. The pH of the extracted soil solution was 7.6. The solution was made from analytic grade reagents and ultra-pure water. All tests were conducted at room temperature of about 22 °C.

2.2. Electrochemical measurements

Fig. 1 shows the home-designed experimental setup for DC corrosion testing. There were two cells, i.e., anodic cell and cathodic cell, to simulate the anodic and cathodic zones during DC corrosion of pipelines. Two different electric circuits, i.e., DC stray current circuit and CP circuit, were included in the setup, where the DC system was under galvanostatic control and the CP system was under potentiostatic control. In the DC current circuit, two carbon rods, which were used as counter electrodes (CE) in the anodic and cathodic cells, were connected to the negative and positive poles of a DC power supply, respectively. The steel specimens, which were used as working electrodes (WE) in both cells, were connected through a slide rheostat to form a closed stray DC circuit. The DC current density flowing between WE and CE was varied, i.e., 0, 0.1, 0.5, 1, 2, 5 and 10 A/m^2, by adjusting the voltage output of the power supply. As the DC output was under control galvanostatically, the DC current density would maintain constantly in order to investigate the effect of DC current density on pipeline corrosion. It was realized that, in reality, the change of soil conductivity will change the DC current density flowing on the buried pipeline, and thus the DC corrosion.

In the CP circuit, the steel specimen and a carbon rod were connected to the negative and positive poles of another DC power supply, respectively. A saturated calomel electrode (SCE) was used as reference electrode (RE), which was immersed into a Luggin capillary. The distance from the tip of the capillary to the steel electrode surface was 2 mm in order to eliminate the ohmic drop. It was noted that the potential of the steel cannot be maintained at the applied CP potential when the DC circuit was ON. In other words, the potential would deviate from the applied CP potential under the DC effect (i.e., the potential of the steel did not automatically adjust itself to the applied CP potential). The potential of the steel electrode under various DC densities was measured through a Gamry Reference 600 electrochemical system. The recorded potential of the steel included both the applied CP potential and the potential shift under DC stray current. All potentials in this work were converted to CSE to be consistent with the industry use.

During testing, the test cells were continuously purged with air to maintain the constant dissolved oxygen content in the solution. A dissolved oxygen sensor was used to monitor the content of dissolved oxygen, which was 7.7 ppm. A pH meter (Oaklon Acorn) was installed to monitor the solution pH at the anodic and cathodic cells. To ensure the reproducibility of the measured data, each test was conducted three time.

2.3. Weight-loss testing

Prior to weight-loss testing, steel coupons were weighed by an electronic balance with an accuracy of 0.1 mg. They were immersed in the soil solution under the corrosion potential of the steel and two CP potentials, i.e., −850 mV vs. CSE and −1000 mV vs. CSE, respectively, and varied DC current densities. To ensure reproducibility of the testing results, three parallel coupons were used at each condition.

After testing, the corrosion products formed on the steel surface were removed carefully by both mechanical and chemical methods according to ASTM G1-03 [26]. Light scraping and scrubbing was used to remove tightly adherent corrosion products, and a descaling solution containing 500 mL HCl, 3.5 g hexamethylenetetramine and 500 mL distilled water was used in chemical removal procedure. The cleaning process was repeated several times to remove corrosion products thoroughly. After rinsing with distilled water and alcohol, the steel coupons were dried and weighed again. The weight change under specific testing conditions was recorded. The corrosion rate (mm/year) of the steel was calculated from the weight-loss measurements and the testing time.

2.4. Surface characterization

After 48 h of testing in the soil solution at various DC current densities and/or CP potentials, the steel electrodes were removed from the solution, and rinsed with deionized water. The surface morphology of the steel was observed by an optical microscope.

3. Results and discussion

3.1. Potentials of the steel in the soil solution under various DC current densities

Fig. 2 shows the time dependence of the potential of X52 steel electrode in the anodic zone at various DC current densities in the soil solution. In all recorded curves, three potential regions are observed. From 0 to 1200 s, there is no DC applied. The recorded potential is the corrosion potential of the steel in the solution. From 1200 to 2400 s, the DC is applied and the DC-ON potential is recorded. After 2400 s, the DC is stopped and the DC-OFF potential is recorded. It is seen that, upon application of DC, the potential of the steel in the anodic zone is shifted less negatively (i.e., towards the positive direction). The potential becomes less negative with the increasing DC current density. At each DC current density, the potential of the steel is maintained at a relative stable value. When the DC is stopped at the 2400th s, the potential drops rapidly, and then gradually reaches a steady state value, which is approximately identical to the corrosion potential recorded prior to the DC application, i.e., the potential from 0 to 1200 s. At higher DC current densities, the potential recovery to the steady value is a bit slower.

Fig. 3 shows the time dependence of the potential of X52 steel electrode under various DC densities in the soil solution in the cathodic zone. Similarly, before the DC is applied, the steel is in its corrosion potential of about −800 mV vs. CSE. Upon application of the DC current density, the potential of the steel is shifted negatively and remains at a constant value. As the increasing DC current density, the potential tends to be more negative. When the DC is stopped at the 2400th s, the DC potential is shifted towards the positive direction, but does not return to the corrosion potential