



# Numerical simulations of soil physicochemistry and aeration influences on the external corrosion and cathodic protection design of buried pipeline steels



Ibrahim M. Gadala<sup>a,\*</sup>, Magd Abdel Wahab<sup>c</sup>, Akram Alfantazi<sup>a,b</sup>

<sup>a</sup> Department of Materials Engineering, The University of British Columbia, 309-6350 Stores Road, Vancouver, B.C. V6T 1Z4, Canada

<sup>b</sup> Department of Chemical Engineering, The Petroleum Institute, Abu Dhabi, United Arab Emirates

<sup>c</sup> Laboratory Soete, Ghent University, Technologiepark, Zwijnaarde 903, Ghent 9000, Belgium

## ARTICLE INFO

### Article history:

Received 14 October 2015

Received in revised form 25 January 2016

Accepted 21 February 2016

Available online 24 February 2016

### Keywords:

Soil corrosion

Pipeline steel

Oxygen transport

Cathodic protection

Polarization

Finite element method

## ABSTRACT

Corrosion of oil and gas transmission pipelines is a serious industrial problem with potentially catastrophic environmental and financial consequences. A finite element model of the external corrosion of buried steel pipelines at coating failures is developed here to better predict degradation in different soil and cathodic protection (CP) environments. Synergistic interactions between steady-state temperature, potential, and oxygen concentration profiles in the soil surrounding the pipeline structure are quantified and discussed. Conductivity and oxygen diffusivity of soil conditions are represented as functions of soil matter, air porosity, and volumetric wetness. Theoretical formulations are uniquely merged with corrosion experiments conducted on actual pipeline steel samples, greatly improving simulation results. Overall, drier sand and clay soil structures cause the most corrosion, whereas wetter conditions impede oxygen diffusion and significantly augment hydrogen evolution. Geometric location of the coating breakdown site relative to the ground surface and the CP anode has a particular influence on oxygen concentration profiles and pipeline corrosion. Model convergence is tested with a mesh sensitivity study, and the model's ability in evaluating practical design changes in the CP system is demonstrated.

© 2016 Elsevier Ltd. All rights reserved.

## 1. Introduction

Industry reports reveal that external corrosion accounts for approximately 40% of structural integrity problems in oil and gas transmission pipeline networks [1]. External corrosion mitigation strategies revolve around two methods: cathodic protection (CP) and protective coatings [1,2]. Chemical degradation of pipeline steels at coating failure sites is lessened by CP systems, in which performance is heavily affected by physicochemical soil properties. Spatial- and time-dependent soil corrosivity is related to numerous physicochemical properties including: position of water table, soil moisture content, soil type, soil resistivity, soil pH, soluble salt content, structure-to-soil potential, redox potential, microbes in the soil, and stray currents [3]. Complexities arise from the interdependence of electrical resistivity, oxygen (O<sub>2</sub>) diffusivity, or heat transfer on one or more soil properties such as particle distribution, porosity, moisture, and temperature [4].

Empirical correlations for predicting soil corrosivity often intentionally overlook certain soil parameters for simplicity. Merely soil's resistivity is considered by some to be a sufficient predictor of corrosivity [5], whilst others consider soil type and structure as the determining factors,

regardless of position with respect to the water table [6]. Empirical limits separating corrosivity categories have been postulated, such as a minimum of 20 wt% moisture content for the "non-aggressive" category [5]. Such empirical guidelines unduly simplify gas transport, heat transfer, and reaction kinetics phenomena (and complex interdependencies therein), making them generally inadequate for detailed evaluations. Instead, numerical simulations can capture a larger spectrum of the fundamental processes occurring on corroding pipelines and better predict perilous operating parameters and critical corrosion locations on exposed surfaces.

Numerical models and simulations of CP and the corrosion of buried/immersed metals have previously been reported [7–9]. In the work of Rabiot et al., a finite element model was used to compare the relative influence of coating quality, soil electrical conductivity, and CP anode size, position, and type on the corrosion of buried steel tanks [7]. The soil's electrical conductivity played a leading role in consequent corrosion, yet the model did not consider other important soil parameters. The work of Miltiadou and Wrobel incorporated the influence of diffusion-controlled O<sub>2</sub> reduction with electrolyte conductivity, and the distribution of electrical potential within the electrolyte was computed [8]. Yet, spatial- and time-dependent differences in electrolyte properties were not accounted for in their uniform and non-porous electrolyte. In porous soil, tortuous mass-transfer obeys multi-phase flow laws which depend on air-filled void porosity, moisture content, and temperature.

\* Corresponding author.

E-mail address: [im.gadala@gmail.com](mailto:im.gadala@gmail.com) (I.M. Gadala).

These parameters are interrelated and depend on other conditions such as soil type and structure, for both the transport of  $O_2$  and charge.

Previous numerical models of CP and corrosion systems often make narrow use of experimental diffusivity measurements. Rather, the rate of transport is determined with empirical parameters [9,10]. Seldom do models present coupled gas transport and electrolyte potential distribution like in [11] or variable gas diffusivity in bulk porous media like in [12]. The present work uniquely simulates the variable diffusivity of  $O_2$  within soil based on established soil science models. For charge transport, the Nernst-Planck formulation relies on concentrations, diffusivities, and electric mobilities of ionic species within the soil. This method is simplified to a governing equation with a single soil conductivity parameter (spatially variable, based on experimental measurements) due to difficulties in quantifying Nernst-Planck variables for irregular soils [7–12]. The conductivity is adjusted for the temperature and moisture content of the soil in each simulation.

Reaction kinetics at electrode-electrolyte interfaces are vital in any corrosion model. Formerly, problems in obtaining reliable kinetic parameters have led to a wide range of values being used. Dependable parameter values can be obtained from experiments run in conditions simulating a specific system. Muehlenkamp et al. [13] reported using parameter values for their modelled system from measurements. In almost all such previous works though, a prescribed number of parameter values are extracted from the experimental results based on the type of formulation intended to govern reaction kinetics. Incongruities between the kinetics model and the actual experimental data are inevitable. In the present work, such discrepancies were eliminated by integrating the full spectrum temperature-controlled polarization results into the model. Critical temperature influences shown before by the authors [14,15] were carried through from the heat transfer results. This feature enables more accurate predictions of CP effectiveness and material corrosion. To our knowledge, it is novel to the model presented here. Overall, the model developed allows for the study of synergistic interactions between heat transfer, charge transport,  $O_2$  diffusion, and corrosion of buried pipelines, with implications on CP and pipeline system design.

## 2. Experimental and modelling details

### 2.1. Polarization experiments

Polarization experiments were conducted on an API-X100 pipeline steel specimen (0.1 C; 0.19 Mo; 1.66 Mn; 0.02 Al; 0.13 Ni; 0.25 Cu; 0.02 Ti; 0.016 Cr; 0.003 V; 0.043 Nb [wt%], balance Fe). The steel specimen was attached to a wire using silver conductive epoxy and set in a hard encapsulating epoxy. Only the flat front face of the specimen ( $0.75 \text{ cm}^2$ ) was exposed to test solutions contained in a 1 L glass jacket test cell. Before immersion, the specimen was sequentially wet-ground to 1200 grit, degreased by sonication in acetone for 10 min, washed with ultra-pure deionized water, and air dried. All experiments were run using a PAR Versastat 4 potentiostat.

Microstructural examination of the X100 steel was performed using a Nikon EPIPHOT 300 series optical microscope and ImageJ analysis software. Polishing was performed with 6 and  $1 \mu\text{m}$  diamond suspension abrasives. Samples were then etched with freshly prepared 2% nital (2 mL nitric acid and 98 mL ethanol) or LePera solution [16] (1:1 ratio of 4 g picric acid in 100 mL ethanol and 1 g sodium metabisulfite in 100 mL deionized water, mixed immediately beforehand) to reveal ferrite or martensite-retained austenite (M-A) phases, respectively. Samples were etched for  $\sim 15$  s in 2% nital or for  $\sim 35$  s in LePera solution.

The jacketed cavity of the glass test cell was connected to a water bath set to either 303 or 323 K (30 or 50 °C), representing the typical minimum and maximum pipeline wall temperatures [17] considered in this study. A slender graphite rod was used as the counter electrode, the X100 specimen as the working electrode, and a Saturated Calomel Electrode (SCE) as the reference electrode, isolated in a salt bridge.

The electrolyte for all experiments was NS4 simulated soil solution, of a chemical composition which can be found in [14]. Immediately following immersion, the working electrode was cathodically cleaned for 60 s at  $-1.5 V_{SCE}$  to eliminate any air-oxides. It was then left to freely corrode for 3600 s, followed by a linear polarization resistance (LPR) test to evaluate anodic kinetics, implemented within  $\pm 10$  mV of open circuit potential (OCP) at a standard scan rate of  $1/6 \text{ mV s}^{-1}$ . After a short OCP re-stabilization session, potentiodynamic polarization (PDP) was scanned on the static specimen in the anodic direction at  $1/6 \text{ mV s}^{-1}$ , from  $-1.25 V_{SCE}$  to  $0 V_{SCE}$  (high anodic potentials are not of interest in this paper).

### 2.2. Model setup

Comsol Multiphysics® version 4.3a is the modelling software used in this study, in which the established Finite Element Method (FEM) is the numerical technique employed. The presence of spatially varying governing properties in this work (e.g.  $O_2$  diffusivity) is a key reason why FEM was favored over other techniques such as the Finite Difference Method (FDM) or the Boundary Element Method (BEM). FDM has inadequate resolution capabilities, plus difficulties in handling irregular meshes and nonlinear effects, while BEM cannot handle the spatially-varying properties of the soil media modelled here.

#### 2.2.1. Geometry and mesh

A three-dimensional (3D) representation of a sectioned buried CP-pipeline system is shown in Fig. 1a. A cross-section of this structure is taken at plane a-a resulting in the two-dimensional (2D) section shown in Fig. 1b, which is the basis of this study. The reduction of the 3D geometry to a 2D one permits the use of 2D plane elements and significantly simplifies the model. Consequences of this simplification on simulation results are discussed in Section 3.6. Dimensions in the model are the typical values for onshore transmission pipelines [18] in excavated ditches [19]. A  $90^\circ$  arc of the steel is exposed to the corrosive soil environment, representing a site where the protective coating completely deteriorated (shown between A and B in Fig. 1b). Although the overall size of this defect is larger than would normally be present on a buried pipeline (aside from disbondments of polyethylene tape coatings along girth weld seams), it is modelled in this way here to identify the varying potential, anodic/cathodic current density, and  $O_2$  concentration distributions at different angles  $\theta$ . In practice, a single simulation result from the present study can be used to evaluate the disparity between CP and corrosion at  $0^\circ \leq \theta \leq 90^\circ$ , instead of running separate simulations for each location. Although the influence of localized corrosion is diminished with this approach, the model maintains the ability to investigate localized effects if desired by reducing the coating defect size. In this study also, discretization versatility of the FEM is exploited by solving 5 sets of mesh resolutions (Table 1) for all simulated parameters. Field variables within each element are linear. All the meshes were discretized finer around electrode-soil interfaces and the ground surface boundary for enhanced identification of critical phenomena occurring between the CP anode, ground, and the pipeline's exposed surface.

#### 2.2.2. Heat transfer, charge transport, and $O_2$ diffusion

Sand, clay, and peat soil structures were modelled in this study, at moisture contents (herein termed volumetric wetness,  $\psi$ ) ranging from 0.1 to 0.6 depending on air porosity ratios ( $\phi$ ). The thermal parameters studied in this investigation are listed in Table 2 [20] and have been experimentally validated [21]. The governing equation for heat flow in the soil (Eq. (1), Table 3) is a function of thermal conductivity ( $\lambda$ ), volumetric heat capacity ( $C_v$ ), and density ( $\rho$ ), where T is temperature [°C], t is time [s], x is the spatial parameter [m], and Q is a constant heat flux density [ $\text{W m}^{-2}$ ] in the presence of heat sources or sinks. Values of  $\lambda$  in Table 2 incorporate latent heat transfer to reflect all heat transfer modes. Air's contribution to  $C_v$  can generally be neglected since  $C_{\text{air}} = 0.0012 \ll C_{\text{water}} = 4.18 \text{ MJ m}^{-3} \text{ K}^{-1}$  [22].

Download English Version:

<https://daneshyari.com/en/article/828078>

Download Persian Version:

<https://daneshyari.com/article/828078>

[Daneshyari.com](https://daneshyari.com)