A comprehensive predictive corrosion model incorporating varying environmental gas pollutants applied to wider steel applications

Mian Hammad Nazir [a, *], Adil Saeed [b], Zulfiqar Khan [a]

[a] NanoCorr Energy and Modelling Research Group (NCEM), Bournemouth University Talbot Campus, Poole, Dorset, BH12 5BB, UK
[b] Global College of Engineering and Technology, P.O.Box 2546, CPO Ruwi 112, Muscat Sultanate, Oman

H I G H L I G H T S

- A comprehensive model is developed to predict corrosion rate of structural steel.
- The effect of pollutant gas i.e. SO_2 on steel corrosion is considered.
- Simulations were performed under varying environmental and physical parameters.
- Experiments were performed by exposing steel samples to moist SO_2 corrosion test.
- Predictions and experimental results comparison validated the model reliability.

A R T I C L E   I N F O

A B S T R A C T

A comprehensive model has been developed to predict uniform corrosion rate of structural steel under the effect of low pH conditions for example, acid rain. Acid rain is mainly caused by emissions of sulphur dioxide (SO_2) which reacts with the water droplets in the atmosphere to produce acidic solution which is the primary cause of corrosion of steel structures such as bridges, high value assets, weathering of stone buildings and statues. A five-stage approach was applied to mathematically describe the model as: (i) the growth rate of air-suspended water droplets (i.e. moisture) depending on the condensation/evaporation rate, (ii) the absorption of gas phase SO_2 in the droplets forming bisulfite HSO_3^- ions, (iii) the coalescence of these SO_2 absorbed water droplets under the effects of wind speed and gravity, (iv) the deposition rate of SO_2 absorbed droplets on steel substrate depending on the inclination and azimuth angles of steel surfaces and, (v) the corrosion rate of steel due to the deposition of these SO_2 absorbed droplets. The incorporation of all of the above stages develops a comprehensive corrosion prediction model which includes both the electrochemical parameters and large number of physical, environmental and material parameters. Experiments were performed to analyse the corrosion rate of steel samples by exposing them to moist SO_2 corrosion test. A comparative analysis between the modelled predictions and experimental results was performed to verify the reliability of the model. The predictive trends of corrosion rate of steel were also generated for various values of temperature, relative humidity and SO_2 mole percentage. This research provides design solutions and guidelines against degradation due to aggressive application environments. Enhanced corrosion resistivity within large structures, installations, automotive, locomotives, aerospace and building with historic biography will aid longevity and cost savings.

© 2017 Elsevier B.V. All rights reserved.

1. Introduction

Previous investigation of coating failures, i.e. blistering, delamination, micro-cracks and corrosion damage measurement in real time has been reported [1-15]. Recently a simplistic model of variation in environmental parameters to understand the effects of changing relative humidity and temperatures in terms of corrosion initiation and propagation on bare steel samples has been published [8]. In this paper a predictive model for corrosion of steel considering corrosive species i.e. sulphur, which has implications
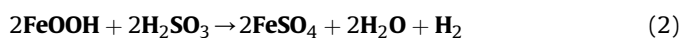

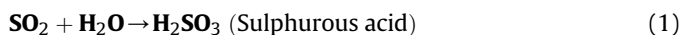on the durability of products and systems in the wider steel applications has been developed and presented.

The accumulation of water vapours as electrolyte on surfaces to initiate corrosion has been widely considered, but little or no work has been conducted on dynamics of the accumulation of vapours such as pressure gradients, gravity, speed and orientation of surfaces relative to vapour deposition. This research combines corrosion initiation and propagation incorporating sulphur as an environmental pollutant, its effects on steel and considers microdynamic vapour pressure concepts into its modelling techniques.

This paper is part of the wider project to obtain reliable data for long term service and a symmetric approach to minimise structural deterioration because of chemical and mechanical wear [1-14]. Both mechanisms when work alone or in combination poses risk of component failures in normal and/or aggressive environments.

Industrial atmosphere contains SO_2 as a major contaminant which poses a great threat in-and-around the larger industrial sites, not only due to its toxic nature but also in terms of structural deterioration as a result of intense corrosion under high acidic (low pH) conditions for example acid rain [16]. When acid rain and dry acid particles fall to earth, sulphuric/sulphurous acid that makes the particles acidic can land on culturally important objects such as statues and monuments, buildings, and other manmade structures such as bridges, and damage their surfaces. The acid particles corrode metal and cause paint to deteriorate more quickly. Aircraft industry also faces serious challenges, when it comes to the operating conditions of aircraft. For example, all aircraft are liable to have dissolved solutions of acidic gases from pollution as well as engine exhaust gases [17]. The rate of corrosion in the presence of SO_2 increases in the company of moisture. SO_2 in the presence of moisture gets converted in to H_2SO_3 (eq. (1)) which upon reaction with oxyhydroxide formed initially, gives corrosion product $FeSO_4$ (eq. (2)). Much of the SO_2 is converted to SO_3 in the upper atmosphere.

$$SO_2 + H_2O \rightarrow H_2SO_3 \text{ (Sulphurous acid)} \tag{1}$$

$$2FeOOH + 2H_2SO_3 \rightarrow 2FeSO_4 + 2H_2O + H_2 \tag{2}$$

Worldwide SO_2 emission data shows that the overall SO_2 concentrations in East Asia (China, Mangolia, South Korea and Japan) show increasing trends [18] which in turn results in the increasing trends of acid rain (pH) in East Asia (major cause of corrosion failure). Moreover, a recent study showed that, between 2005 and 2014, SO_2 emissions in India has gone up by an enormous 71% from what it was in 2005 [19]. Although, SO_2 emission in US has decreased by 34% (according to department for US Environmental Protection Agency [20]), and in UK by 65% in past 10 years (according to department for Environment Food & Rural Affairs [21]), but still, SO_2 emission poses a great threat near industrial areas (for example parts of London and Glasgow, Cardiff, Swansea and Port Talbot) in terms of high corrosive degradation of metal structures [16].

This research develops a comprehensive predictive model for structural steel corrosion in SO_2 contaminated atmosphere. However, for simplicity, the present study is mainly focused on investigating the laboratory experimental conditions related with the corrosion problems of structural steel AISI 1010 with $SO_2-O_2-H_2O$ impurities. The model can be used to simulate the real industrial environments, as the model is equally applicable for predications of wider steel types (such as Ferritic, Austenitic, and Martensitic) under multiple gases pollutants (such as carbon monoxide, nitrogen dioxide and lower atmosphere ozone). This model also helps in corrosion predictions by considering the dynamics of accumulation of SO_2 enriched water vapours such as pressure gradients, gravity,

wind speed and orientation of steel surfaces relative to vapour deposition. The experiment was performed to analyse the corrosion rate of steel AISI 1010 in moist air containing SO_2. The model predictions were compared with the experimental results to verify the reliability of model.

Some models such as [22,23] predict the corrosion of mild steel in thin water film with SO_2 diffusion. However, these models only simulate the corrosion mechanism by assuming certain value of thin water film thickness at the start of model. This assumption eventually evades the effects of many vital pre-water deposition parameters (physical, environmental) which may directly affect the thickness of water film deposition on steel surface and eventually could significantly change the corrosive reactions due to SO_2 diffusion. Our model fills this gap by considering pre-water deposition parameters and linking them to post-water deposition corrosive reactions.

2. Experimental

2.1. Samples preparation

A thin carbon steel (AISI-SAE-1010) substrate with thickness s = 0.05 cm was used to prepare three test samples with dimensions 15 cm × 10 cm each. The reason for selecting AISI 1010 is its wide applicability for numerous general engineering and structural applications. During the process of samples preparation, no chemicals were used. The chemical composition of the AISI 1010, by % weight, is: C (0.13%), Si (0.05), Mn (0.60%), S (0.050%), P (0.040%) and balanced Fe (99.18%) [24]. The surface conditioning of steel samples was performed by using polishing wheel with emery paper of 200 grit size to achieve an average roughness (Ra) of 0.193 μm. After polishing, the conditioned samples were cleaned with a 35 min immersion into a constantly stirred solution of 50 g/L Turco 4215 NC-LT. After completing this alkaline cleaning the samples were rinsed with deionized water and air dried. Weight was recorded to the nearest fifth significant figure and the steel samples were stored in a desiccator. To ensure the repeatability, the experimental data was collected from three samples each adhered with corrosion sensor with dimensions 40 mm × 20 mm x 0.1 mm [25]. All the samples were adhered with the corrosion sensors in order to monitor the corrosion rate in real time (Fig. 1 (a)). The sensors were connected to the data acquisition unit (DAQ) (Fig. 1 (b)), from where the data was retrieved in PC by using a wired interface (RS232). The software, installed in PC, converts LPR and resistance data into a corrosion rate. The sensors consist of multiple plates made from the material of interest which form the three electrodes. The electrodes are used in conjunction with a potentiostat for conducting LPR measurements. The use of a relatively large counter electrode minimizes polarization effects at the counter electrode to ensure that a stable reference potential is maintained throughout the experiment. Potential step-sweeps are performed by applying a series of 30 steps over a range of ±10 mV spanning a period of 2.6 s [26]. Corrosion sensors measure the polarization resistance $R_p(\Omega)$ between the corrosive agents (electrolytic solution) and the steel samples. The polarization resistance is then used to calculate the corrosion current density 'i' at the interface by using Stern-Geary equation as [27],

$$i = B/R_p \tag{3}$$

Where, B is called Stern-Geary constant. The corrosion current density 'i' is measured from the polarization resistance values by using a Stern-Geary constant of 30 mV for carbon steel [24]. The corrosion current density 'i' is used to calculate the corrosion rate (mm/year) by using following eq.