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Effects of shear stress on the erosion-corrosion behaviour of X-65 carbon steel: A combined mass-loss and profilometry study

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ABSTRACT

A combined mass-loss and profilometry techniques was undertaken with the goal of understanding the role of high shear stress on the erosion-corrosion behaviour of X65 carbon steel in a submerged impingement jet (SIJ) system. Computational fluid dynamics (CFD) enabled an accurate prediction of a range of shear stresses (80, 280, 570 Pa) and particle tracking (0, 200, 500 mg/L) across the sample surface with inhibitor concentration (0, 100 ppm). The results demonstrated the suitability of combining mass–loss and surface profilometry techniques for quantifying and predicting general and localized corrosion of X65 pipeline material in an erosion–corrosion environment.

1. Introduction

The fast depletion of most natural oil and gas reserves encourages tapping of deposits that are regarded as unproductive, complex, and multiphase in nature (due to the merging of oil and gas with water, gas – CO_2 and H_2S, solid – sand and shale and other impurities). The multiphase nature of these reserves may result in erosion–corrosion phenomenon with its attendant mechanical and electrochemical degradation processes. Scholars have researched into erosion–corrosion with a view to understanding its nature [1–12]. The multiphase environments lead to adverse conditions (high shear stresses and effects of solid particles) such that the productivity is significantly affected. Several mechanisms have been adduced for erosion–corrosion but the most studied is the erosion, corrosion and their synergistic effects [3,13–17]. It has also been reported that the degradation can be either general or localized with the former being safe, measurable and controllable; whereas, due to the depth, size and other variables, localized attack is complex in nature [18–19]. Less information exists on the localized mode of attack despite its prevalence in multiphase environment even in the presence of chemicals [20].

Chemical mitigation is advocated in preventing and controlling erosion–corrosion in oil and gas industry [2,3]. Considerable progress in the understanding of erosion–corrosion mechanisms has been achieved through inhibitor addition either by the adsorption of the inhibitors on the sand or on the metal surface. Equally, work has advanced on the role of these chemicals on the effect of solid particles and hydrodynamic parameters such as flow velocity, shear stress, among others [1–3,9,21–22]. The consensus is that the introduction of inhibitor can only retard general corrosion at the expense of localized attack [20]. This genuine concern is due to the challenge posed by the measuring technique that can cater only for localized corrosion despite several ways to estimate degradation rates in multiphase system. Several researchers have used a range of standard laboratory techniques to evaluate erosion–corrosion and jet impingement technique has been adjudged to give good degradation rates for various hydrodynamic parameters [2–4,9,11,23–25]. Extensive studies have been carried out to understand the flow pattern on the impinged surface and detailed mathematical relationships have been reported. A study concluded that the flow field distribution and shear stress on the electrode surface have pronounced effects on the corrosion of the steel [23].

A common tool widely used to study various flow regimes and solid particle motion is CFD [6,7,26–29]. It has been demonstrated that experimental data obtained from JIT can be correlated with simulated CFD to predict the flow regime and solid particle activity. The results showed that the predictions were accurate [6,9,22]. Another study combined weight-loss technique and computational fluid dynamic simulation to determine the roles of fluid mechanics and solid particles in erosion-corrosion of steel pipe in oil sands slurry [29]. Traditionally, gravimetric technique is commonly used by researchers and industrialists to evaluate erosion-corrosion. The understanding is that this technique is not applicable to localized corrosion due to insignificant mass loss and inability to determine the penetration depth [18–19].

In order to further understand erosion–corrosion, there is a large volume of literature on the use of in-situ electrochemical

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measurement to provide information on electrochemical degradation and the synergistic effects [1,7,14,15,30,31]. Little attention has however been paid to the effect of shear stress and solid particles in uninhibited and inhibited environments. In a previous work, the influence of high shear stress and particle loadings on the degradation rate of X65 carbon steel in blank and inhibited conditions was assessed through the application of electrochemical techniques [22]. The common point is that most electrochemical measurements are related to the general corrosion rate and that localized corrosion measurement is difficult to quantify due to alteration of the environmental chemistry locally, electrode geometry, and the surface area [18–20].

The purpose of this paper is to highlight the effects of high shear stress in the presence of solid particles on blank and inhibited multiphase systems, with additional information on general and localized attacks. It is obvious that research efforts have concentrated on general corrosion without showing the threat associated with localized attack on carbon steel. A review of the literature relating to localized corrosion measurement has shown that profilometer is the most employed facility. The focus has been on penetration depth [14,15,32–34], wear profiles [28] and surface profile [35]. Recently, a work employed a profilometer to assess the localized attack using the mass loss from pit depths by taking an average of 10 deepest pits. It demonstrated the need to quantify localized attack and emphasized that mass loss measurements data are most often misleading [36].

In this study, the overall objective is to evaluate the damage associated with erosion corrosion in oilfield environment through the integration of profilometry and gravimetric measurements. The study further contributes to the understanding of the role and extent to which shear stress and solid particles played in affecting degradation rate.

2. Experimental details

2.1. Materials

The material used in this study is API 5L X65 carbon steel which is one of the most employed in oil and gas industry (with Vickers hardness of 228 HV) due to its high performance and low cost [9,17,37]. The chemical composition was determined according to spark Optical Emission Spectroscopy (OES) technique at Sheffield Testing Laboratories, UK and the chemical composition is presented in Table 1.

The samples geometry for the SIJ test was cylindrical with diameter of 25 mm and 15 mm thickness with exposed area to the impingement jet of 4.09 cm^2 and the remaining area was covered by epoxy coating. Each specimen was polished with 1200 silicon carbide paper, degreased in acetone, rinsed with distilled water and dried with compressed air before the commencement of every test.

2.2. Solution preparation

The process fluid was prepared according to the work of Hu et al. [38], sparged with CO_2 for a minimum of 12 h to achieve an oxygen concentration of below 20 ppb simulating the oilfield conditions. The vessels were sealed in every test and CO_2 was bubbled into the system throughout the experiment to maintain CO_2 partial pressure at 1 bar. The pH was measured to be approximately 5.5 and a small increase of about 0.2 was observed at the end of the tests.

Table 1
Nominal compositions of API 5L X65 carbon steel (wt%) [7].

Elements	C	Si	Mn	P	S	Cr	Mo	Ni	Ti	Fe
Mass%	0.10	0.18	1.21	0.009	0.003	0.10	0.16	0.07	< 0.01	Balance

2.3. Inhibitor and sand particles

A commercially available CO_2 inhibitor formulated for high shear environment was used in this study. The chemical package is based on a combination of anhydrides, polyamines, ethoxylated imidazolines, quaternary ammonium salts, ethanodiol and thioalcohol. The inhibition concentration was tested at 100 ppm for all the experiments based on the report of an earlier study [22]. The focus of the study is to show that introduction of inhibitor mitigates the rate of degradation. This work does not make any attempt to relate the inhibitor concentration with its chemistry.

Tests were conducted with solid loading of 200 and 500 mg/L of sand to create an erosion–corrosion environment. Round silicon sand particles which are un-ground were used in these studies with an average diameter of 250 μm [7].

2.4. Erosion corrosion tests

The erosion–corrosion experiment was conducted using a submerged impingement jet (SIJ) apparatus as shown in Fig. 1. A recirculating system was adopted by the rig which delivers the process fluid through two nozzles which impinge onto flat specimens at an angle of 90°. The nozzles have a diameter of 4 mm with the standoff distance being kept constant at 5 mm. Velocities chosen for the tests were 5, 10, and 15 m/s and CFD modeling of the SIJ was adopted to determine the shear stress distribution over the sample surface. The modeling was carried out as earlier reported [5] whereby the model for the SIJ is assumed to be axisymmetric about the centerline of the pipework (Fig. 2). The CFD model generated the following shear stresses for the various velocities; 80, 280, and 570 Pa for 5, 10, and 15 m/s.

Prior to commencement of the experiments, the specimens were weighed with precision weighing scale and after exposure; the samples were rinsed with water, cleaned with Clarke's solution, and weighed to determine the mass loss. All experiments were conducted for four hours at a temperature of 50 °C. The summarized operating parameters are as presented in Table 2.

2.5. Surface analysis

The post-test analysis of the material damage mechanisms were examined by a profilometer. This experimental technique was used to clarify the effect of the sand loading, the absence and presence of inhibitor, and shear stress on the specimen's surfaces (e.g. volume loss); and particularly to determine the mass loss associated with each sample. The equivalent mass loss is measured post-test by contact profilometry. It is given as the volume loss divided by density of the material [39]. In fact, this is the methodology that was proposed in the ASTM G76 [40]. Parameters such as penetration depth, wear profiles (2-D and 3-D), wear scar volume, and maximum depth were measured. The profilometer used in this study was Taylor Hobson Talysurf Ultra Precision measurement system PGI 800 Digital Surf's MountainsMap® 6 with software packages using ISO 25178 [41] standards for the surface metrology analysis.