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Long-term under-deposit pitting corrosion of carbon steel pipes

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ABSTRACT

Some steel water injection pipelines used to increase the yield from oil production reservoirs in the offshore oil industry have experienced severe channelling corrosion at the 6 o′clock position. The examination of field observations suggests both under-deposit corrosion (UDC) and microbiologically influenced corrosion (MIC) are likely to be associated with the phenomenon. Long-term laboratory experiments are described to distinguish the relative contributions of the presence of deposits, MIC and nitrate addition to the formation of channelling corrosion. Half-pipe steel specimens were exposed to different simulated test environments up to 365 days. The analysis of pitting morphology and pitting depth shows the synergistic effect of MIC and under-deposit corrosion led to severe localized corrosion. Nitrate addition caused most severe localized corrosion. Extreme value distribution examination shows Gumbel function is not appropriate to describe all the pit depth data for 1 year exposure. The results have implications for the corrosion management in industrial practice.

1. Introduction

Water injection is the most commonly used method to increase the yield from oil and gas reservoirs. Seawater is typically the most convenient water source, and aquifer water and produced water (recovered from crude oil) or some combination is also used (Comanescu et al., 2016). The choice depends mainly on availability and economics. Fig. 1 shows a schematic view of a water injection system in offshore oil production. The water injection pipelines (WIP) usually are carbon steel and often are many kilometres long. Because the insides of the pipes usually are not coated, the adverse operational environment means that internal corrosion is an on-going problem for many water injection pipelines. In practice, a variety of corrosion mitigation approaches have been attempted. Usually physical and chemical de-aeration of the water is applied so as to reduce the dissolved oxygen to a very low level (typically <20 ppb) as this is considered to reduce the availability of oxygen in the corrosion process. Prior to injection, the water is also filtered to attempt to remove most of the solid impurities, such as sand or shells. Some, but not all, operators use regular or irregular pigging to remove the solid impurities on the interior surfaces to attempt to control microbiologically influenced corrosion (MIC). Surface deposits are considered to create environments suitable for sheltering potentially aggressive microbes (Comanescu et al., 2016; Heidersbach and van Roodselaar, 2012). In many cases nitrate ($Ca(NO_3)_2$ or $NaNO_3$) is added to the injected water to control the production of H_2S by suppressing the metabolism of sulphate reducing bacteria (SRB) (Stott, 2012). Field observations show that these practical approaches mitigate internal corrosion to various degrees but do not eliminate it (Comanescu et al., 2016).

A corrosion problem of much concern in practice is the severe internal corrosion at the lower part of water injection pipelines in near-horizontal positions, in some cases, severe metal loss threatening the integrity of the pipeline, noting that internal pressures might be around 800 MPa. This type of corrosion is known variously as channelling corrosion, 6 o′clock corrosion, and bottom of the line corrosion. Channelling corrosion typically is much more severe than corrosion elsewhere inside WIPs (Heidersbach and van Roodselaar, 2012). Channelling corrosion has been of concern for some time. Thus in 1997, an investigation of 23 WIPs located in the North Sea by a Joint Industry Project (Maxwell, 2006) indicated that 9 of these failed due to channelling corrosion at the 6 o′clock position. Some of these pipelines had been in service only some 4–15 years, even though the typical design service life is 20–25 years. Other failure cases also have been reported (Comanescu et al., 2016; Heidersbach and van Roodselaar, 2012). Despite these industrial reports and conference papers (Heidersbach and van Roodselaar, 2012; Maxwell, 2006), the causative mechanism of the channelling corrosion phenomenon is still not fully understood although an initial proposal has been made (Comanescu et al., 2016). It is based on a detailed analysis of field observations and experience for five representative WIPs located in the Norwegian continental shelf. The analysis included operational parameters (including water velocity, water composition and chemical addition), pigging frequency and observations of bacterial communities. The authors combined field observations and industrial experience with a

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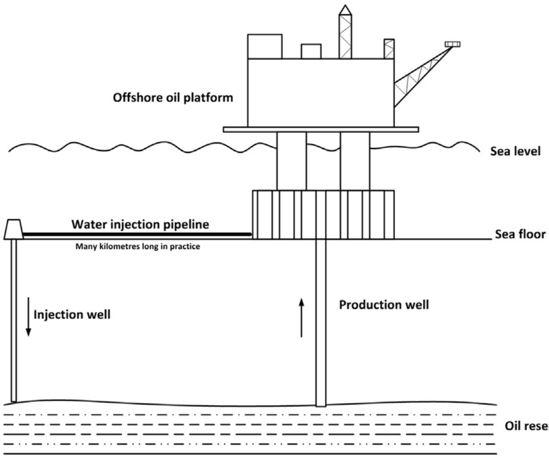

Fig. 1. Schematic view of typical offshore oil production system.

previously proposed corrosion model for carbon steel in natural seawater environments and concluded that: (i) channelling corrosion is associated with the use of seawater and nitrate treatment; (ii) so-called 'under-deposit corrosion', caused by the deposition of pipeline debris, including corrosion products, under low water velocity or even stagnant conditions (during maintenance or replacement work), is the key factor in the development of channelling corrosion; and (iii) microbiologically influenced corrosion (MIC) can play a part in conditions leading to channelling corrosion. These conclusions are consistent with available information and known marine corrosion processes and throw new light on the understanding of channelling corrosion, but some issues, such as the role of MIC on long-term corrosion development and the effect of nitrate addition still warrant further investigation.

Extensive research efforts (Jeffrey and Melchers, 2003; Lee et al., 2004; Little and Lee, 2007) show that MIC contributes considerably to the severe localized corrosion of carbon steel exposed in natural seawater and, as noted, this suggests that the severe localized corrosion of water injection pipelines also is microbiologically influenced (Comanescu et al., 2016; Heidersbach and van Roodselaar, 2012; Stipanicev et al., 2014) and has led to much investigation of the potential role of MIC in WIPs. The case for MIC involvement also is supported by field observations and microbial examination of flush discs recovered from the inside of WIPs that showed much evidence of bacterial activities (Comanescu et al., 2012). Compared with MIC, under-deposit corrosion (UDC) as a cause of channelling corrosion has received much less attention, even though it is frequently reported as a factor in corrosion in other areas of the oil and gas industry. The classic mechanism of UDC in the presence of oxygen is the formation of oxygen concentration cells in which the metal beneath deposits act as anodes (Hinds and Turnbull, 2010). UDC is also possible in the absence of oxygen, with the localized corrosion initiating and propagating under deposit particles as a result of galvanic effects (Han et al., 2013). Moreover, recent observations (Melchers, 2014a) suggest that the aggressive autocatalytic corrosion reactions under anoxic abiotic conditions caused by MnS inclusions (present in all commercial steels) sustain the corrosion process. Provided the critical nutrients for microbial metabolism are available, MIC may then play an additional role by providing aggressive sulphide species (Melchers, 2014a).

In seawater the critical nutrient in MIC is dissolved inorganic nitrogen, usually present mainly as nitrate (Melchers, 2014b). This also applies for fresh waters although other nutrients, present in seawater, may not be available (Melchers, 2006a). Importantly, in the oil and gas industry nitrate often is injected into oil reservoirs to control the production of H_2S by interfering with the normal sulphide generation activity of SRB (Schwermer et al., 2008). Where this is done, the nitrates are injected into the reservoirs by mixing them with the injected water conveyed by the WIPs. However, both successful and failure cases are reported (Beeder et al., 2007; Eckford and Fedorak, 2002; Greene et al., 2003; Halim et al., 2011; Nemati et al., 2001; Stott, 2012; Thorstenson et al., 2002). It suggests nitrate addition may increase the corrosion inside these pipes since recent findings show high correlation between nitrogen-based nutrients and increased localized corrosion (Melchers, 2014b).

The present work reports observations of longer-term corrosion of model steel pipes in a pilot laboratory study aimed at improving the understanding of development of channelling corrosion in offshore water injection pipelines. Half-pipe steel specimens were exposed continuously to stagnant and simulated deoxygenated seawater in the presence of mixed deposits for up to 365 days. The relative contributions of MIC, UDC and nitrate addition to corrosion development were investigated using four different test environments. The steel specimens were recovered after 12, 180 and 365 days of exposure and the changing surface topography was examined by Scanning Electron Microscopy (SEM) and optical microscope. This was to assess the effect of test environments on severity and development of localized corrosion. The progression of maximum pitting depth with increased exposure period was evaluated. The mechanism of the formation of channelling corrosion based on these findings is discussed and a preliminary extreme value analysis of variability in maximum pit depth is presented. The results are considered to provide information directly relevant for optimizing corrosion management of offshore water injection pipelines in practice.

2. Materials and methods

2.1. Test environments

The essential concept in the present study is to investigate the corrosion behaviour of carbon steel under simulated stagnant conditions for a water injection system, with the potential influencing factors, including presence of deposits, microbiological activities and nitrate treatment, taken into consideration. As described below, identical test vessels were constructed to expose half-pipe steel specimens to four different test environments, as shown in Table 1. In test environment 1, which acts as a control, the half-pipe steel specimens were exposed directly to deoxygenated natural seawater. The steel specimens in test environment 2, 3 and 4 were covered with mixed deposits (magnetite, calcium carbonate and sea sand) and exposed to deoxygenated seawater. The seawater filled in test environment 3 was treated with filtration and UV irradiation. 0.25 mM NO_3^- was added to test environment 4 to simulate a practical nitrate addition in real water injection system. For all four test environments, sodium bisulphite ($NaHSO_3$) is used as oxygen scavenger to remove dissolved oxygen.

Table 1
Test environments for exposure of half-pipe steel specimens.

Environments	Water type	Deposit	Chemical treatment	Temperature
1	Deoxygenated natural seawater	No deposit	Sodium bisulphite	30 °C
2	Deoxygenated natural seawater	Magnetite, calcium carbonate, sea sand	Sodium bisulphite	30 °C
3	Filtrated and UV irradiated seawater	Magnetite, calcium carbonate, sea sand	Sodium bisulphite	30 °C
4	Deoxygenated natural seawater with nitrate addition	Magnetite, calcium carbonate, sea sand	Sodium bisulphite, Calcium nitrate	30 °C