Potential for real-time monitoring and control of dissolved oxygen in the injection water treatment process

Durdevic, Petar; Raju, Chitra Sangaraju; Yang, Zhenyu

Published in:
IFAC-PapersOnLine

DOI (link to publication from Publisher):
10.1016/j.ifacol.2018.06.373

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Durdevic, P., Raju, C. S., & Yang, Z. (2018). Potential for real-time monitoring and control of dissolved oxygen in the injection water treatment process. *IFAC-PapersOnLine*, *51*(8), 170-177. https://doi.org/10.1016/j.ifacol.2018.06.373

Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 51-8 (2018) 170–177

Potential for Real-Time Monitoring and Control of Dissolved Oxygen in the Injection Water Treatment Process

Petar Durdevic * **Chitra S. Raju** ** **Zhenyu Yang** *

* *Aalborg Unviersity, Esbjerg, 6700 Denmark (e-mail: mailto:pdl@et.aau.dk, yang@et.aau.dk).*
** *Billund Vand, Grindsted, 7200 Denmark (e-mail: csr@billundvand.dk)*

Abstract: Injection of water into wells is a common practice in offshore oil and gas installations, and here as in many other industries the water has to be deaerated before it is sent through miles of pipelines to reduce the risk of corrosion in those pipelines and other downstream equipment. It requires extremely low concentrations of dissolved oxygen for the corrosion of metals to begin, and removing the dissolved oxygen is currently done in large vacuum deaeration towers, a highly energy demanding process, along with additional injection of chemical oxygen scavengers. In many instances these processes are controlled in a feed-forward manner, where the operators rely on infrequent sampling and corresponding measurements to control the process. The possibilities for optimisation in this field are thus numerous. The main challenges are online measurements of dissolved oxygen and their use in feedback control. This article gives a brief review of the state-of-the-art and investigates the potential of using dissolved oxygen as a reliable feedback parameter, taking inspiration from onshore waste water industries which have been dealing with dissolved oxygen feedback control since the 1970's.

Keywords: Dissolved Oxygen, Injection Water, Deaeration, Oil and Gas, Offshore, On-line Monitoring, Feedback Control.

1. INTRODUCTION

In the early stage of a reservoir's life cycle, the oil production is in its primary production, where the oil is driven from the field by the reservoir's natural pressure, this method can extract from as low as 5% to a typical 30-35% of oil depending on each specific case, Hyne (2012). Then follows the secondary oil recovery where the injection of water through the injection wells is used to increase the pressure in the oil reservoir, this practice was started in the 1980s, Willhite (1986), Lyons and Plisga (2011). The water to be injected into the reservoir is in some cases pumped directly from the ocean, according to Dake (2001) from a depth of 100-200 ft where the plankton level is acceptable for use in the system. The water that is injected could also be recycled produced water, Skinner (1982). Before the water is injected it is de-oxidized and filtered of solid and organic compounds, Dake (2001). For example, the total suspended solids concentration of the injection water pumped from 100 ft below the sea surface in the Faeth Mishrif reservoir was an average of 1 mg/l with a maximum concentration of 5 mg/l, and after several filtering stages the concentrations were reduced to 0.2 mg/l, Nassivera et al. (1979). The filtration is done in accordance to the properties of the geological formations where the water will be applied, for example their pore sizes, chemical and thermal characteristics; and thus the particle sizes that enter with the water must be smaller than those to prevent formation of scale and fouling, Dake (2001).

Another problem of water injection is corrosion, as the water used in most cases comes from the ocean and it contains chemicals that corrode the offshore installations. Dissolved oxygen (DO) is the most common corrosive agent, and it is several times more corrosive than carbon dioxide (CO_2) and hydrogen sulfide (H_2S), Skovhus et al. (2017). One way of reducing corrosion is by using corrosion resistant materials, Donham et al. (1991). While the use of corrosion-resistant alloys (CRAs) has increased since the 1980s, majority of the pipelines are still of carbon steel, Skovhus et al. (2017). As carbon steel is easily corroded, and replacement of all carbon steel into CRAs is not economically viable, alternative forms of corrosion protection are preferred.

The removal of DO is required as it works as a powerful oxidizer in the presence of H_2S, it converts H_2S or FeS into S compounds which are highly corrosive, Skovhus et al. (2017).

Corrosion of metals occurs in the presence of DO, and thus a reduction of DO in the injection water would lead to a reduced corrosion of the facilities, Brondel et al. (1994), Byars et al. (1972). Corrosion of pipelines reduces the pipe's wall thickness, the thinner walls are susceptible to cracking which can lead to leaks and in the worst case, to total damage of the pipelines, Dey et al. (2004). The

---

⋆ The authors would like to thank our colleagues J.M.Kristensen, S.M.Ø.Lauridsen from Mærsk Oil A/S and our colleagues from Billund Vand A/S for technical support.

10.1016/j.ifacol.2018.06.373

presence of DO also oxidizes precipitable solids, which leads to plugging of the well, Byars et al. (1972). DO, in addition, promotes microbiological growth in the reservoirs which is undesirable for effective oil recovery, Devold (2013). Certain bacteria produce polysaccharides which results in the bacteria adhering to each other and forming lumps which can lead to plugging of the injection wells, Popoola et al. (2013). The occurrence of microbial flora can in addition increase the production of CO_2 and H_2S and organic acids which further promotes corrosion, Popoola et al. (2013). In Alvis (1969), the relation between corrosion and DO was measured continuously over a time period of 37 days, where the DO was reduced to 0 mg/l using sodium sulphite catalysed with cobalt as a scavenger, and where at very low DO concentration the corrosion was almost completely halted. The DO level required to prevent corrosion is highly dependent on the individual oil and gas facility and the surrounding conditions. Thus various studies recommend different DO levels to prevent corrosion, for example; Nassivera et al. (1979) recommend 0.02 mg/l and below, and Bradley (1987) recommend DO concentrations below 0.05 mg/l. According to, Byars et al. (1972), oxygen accelerated corrosion occurs when the DO concentration in water is above 0.025 mg/l. One reason for this is that corrosion in greatly reduced in H_2S free water and conversely increases with the concentration of H_2S, Skovhus et al. (2017). Other conditions such as salinity, carbon dioxide content etc. also plays a role in determining the concentration of DO at which corrosion begins to occur. For example, with respect to the Faeth Mishrif reservoir, the dissolved oxygen content in the seawater 100 ft below the surface was 6.5mg/l with a salt level of 42-44mg/l, which results in a highly corrosive environment, Nassivera et al. (1979).

The DO content in seawater is dependent on several parameters such as temperature, pressure, salinity and micro-organism types and activity, Garcia and Gordon (1992), Wetzel (2001), Skovhus et al. (2017). Oxygen concentration in air is 21%, and when it is dissolved in water it follows the dissolution process: $O_{2(g)} \rightleftharpoons O_{2(aq)}$, where the equilibrium can be found through Henry's law constant K_H, Cann (2005).

Corrosion occurs at all stages in the offshore oil and gas fields, and it has a huge economic impact on the industry, its effect is estimated to $170 billion per year in the US alone, Brondel et al. (1994). The reduction of DO is thus highly prioritized in the offshore oil and gas industry, and it can be achieved in different ways.

1.1 DeAeration/DeOxidation solutions

Dissolved oxygen can be reduced using multiple methods which include: chemical scavenging (Oxygen scavengers), gas stripping or liquid extraction, Byars et al. (1972), Flammang et al. (1976), Skinner (1982) and Bradley (1987).

Chemical Scavengers Chemical scavengers are, in most cases, used in cooperation with the mechanical deoxygenation to remove the residual DO using sulphite based scavengers using the following reaction, Robinson (2010):

$$SO_3^{2-} + O_2 \rightarrow SO_4^{2-} \tag{1}$$

The scavengers reduce the concentration of DO thus reducing its corrosive effect on the metals. The commonly used DO scavenging agents include sodium sulfite ($NaSO_3$), sodium bisulfite ($NaHSO_3$), ammonium bisulfite (NH_4HSO_3), sulfur dioxide (SO_2), sodium hydrosulfite ($Na_2S_2O_4$) and hydrazine (N_2H_2), Reis (1996). It is noteworthy that excess of sulfite/bisulfite based oxygen scavengers can for instance feed sulfate reducing bacteria (SRB) Skovhus et al. (2017), which can lead to increased levels of H_2S and thus biogenic sulfide corrosion.

Gas Stripping and Vacuum Deaeration Towers Deaeration is operated on the principle that the amount of dissolved oxygen is proportional to its partial pressure in the gas phase in accordance to Henry's Law, Skovhus et al. (2017), thus by reducing the partial pressure of the gas phase its concentration in the water phase can be reduced, Bradley (1987). This can be achieved in two ways, either using a stripping gas, or by reducing the total pressure of the system, in both cases it is most common to use deaeration towers or columns. A simplified example of an offshore water injection system is shown in figure 1, where the deaeration tower in most cases comprises of multistage towers with the ability to reduce DO to <0.02mg/L; single stage units cannot reduce the DO to such levels Carlberg et al. (1976). The stripping gas is injected at the bottom of the column and the water is injected at the top of the column, where it slowly moves downwards splashing onto a series of trays to increase the retention time, Bradley (1987), Barnhart (1995) The gas stripping brings the injection water into contact with a dry gas stream and different packing materials such as glass marbles or plastic shotgun wadding etc. are used in the deaeration column to enhance the contact area of the gas and liquid, Barnhart (1995). The interaction between the injection water and the stripping gas, strips away the DO from the water as the introduction of other gasses to the water decreases the partial pressure of the oxygen. The water leaves at the water outlet with a low DO concentration, Skinner (1982). The most common gas used is natural gas as it is widely available on the offshore platforms, the drawback being that the gas used for this purpose cannot be used for sales. An additional drawback is that natural gas contains CO_2 and H_2S, (CO_2 = 0-8%

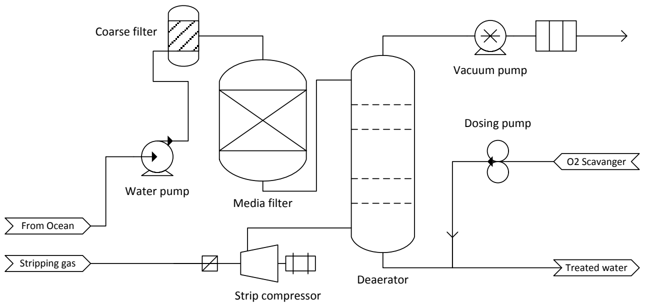

Fig. 1. A typical sea-water injection system on an offshore oil and gas facility, comprising of sea-water filtration, vacuum and gas stripping tower and a downstream O_2 scavenger injection.

and H_2S 0-5%, Holmager (2010)), which reduce the water quality by acidifying it and thus increase the corrosive properties of the water, Henriksen (1985), Donham et al. (1991). Where, CO_2 results in sweet corrosion and H_2S in sour corrosion, Diaz et al. (2010).

In a vacuum deaeration tower, the total pressure inside the tower is reduced to 0.01 bars, Carlberg et al. (1976), which reduces the partial pressure of the oxygen, and thus strips the DO from the water. Gas stripping can be combined with vacuum deaeration to further decrease the DO concentration. But as stripping gas in some cases contains CO_2 and H_2S, vacuum towers are in such cases operated independently of the stripping gas, Bradley (1987).

According to, Byars et al. (1972) water injection systems can be operated DO free, although solely using vacuum tower can only reduce the DO to 0.3 mg/l. Combining it with gas stripping and chemical scavengers is required for lower DO concentrations, Carlberg et al. (1976). Costs, however, can limit an operation to rely on vacuum towers, for example; for a 100,000 b/d operation, a vacuum tower costs 450,000 USD/year when compared to 212,500 USD/year for chemical scavenging, Carlberg et al. (1976). The lack of real-time monitoring systems contributes to an uncertainty of system stability and the transient DO levels which at periods could fluctuate and could be damaging to the installations. Studies have shown that cyclic behavior between anaerobic and aerobic conditions increase corrosion, and can have a more harmful effect than either consistent anaerobic or aerobic conditions, Lee et al. (2005). The introduction of real-time control is thus considered advantageous, although this requires the ability to monitor DO in real-time and feed it back to a control loop which in turn can control one of the following parameters; vacuum, stripping gas flow and/or scavenger flow. Another problem is reduction of deaerator effectivity by e.g. salt deposits, Carlberg et al. (1976), such faults could be detected dynamically using real-time instruments and advanced fault detection methods and resolved continuously. The most obvious parameter to measure is DO, as this is the parameter that we wish to control, but this requires reliable on-line real-time measurements, which are not common practice in the offshore installations. In some cases the corrosion is measured using Linear Polarization Resistance (LPR) using a specific PAIR^{TM} technique, Nassivera et al. (1979), but the dynamics of the corrosion are considerably slower that the one of the DO levels in the system.

This article reviews DO measurements techniques which could be suitable as a feedback parameter in the offshore deaeration process. In addition modeling of the DO is discussed, as it can contribute to parameter estimation. By drawing knowledge from other research fields a simple model that models the significant dynamics of the deaeration process is proposed. Such a model would be an ideal tool for additional system analysis and control development. Finally a control structure is proposed, which comprises of DO based feedback control, inspired by waste water aeration, a thoroughly researched field which has been extensively implemented in the industry. The ideal solution for the offshore installations is to introduce an all software solution, as installing new equipment is expensive. For example, 20 years ago the cost estimate for just the rig support structure for any topside equipment was 20,000£/ton, Peel et al. (1998), where the price today can be up to 50,000 USD/ton for construction of offshore topside production facilities, Emmerson (2018).

2. MEASUREMENT OF DISSOLVED OXYGEN

There are four major methods known for determination of oxygen; the first and second are the Winkler titration and pressure-based methods, which are not applicable in this case as they are laboratory based, the other two methods that could be used for sensing are, electro-analytical, and optical methods Wang and Wolfbeis (2014). Electrochemical methods can include among others polarographic methods, potentiometric methods, coulometric methods and conductometric methods Kalvoda (1984). DO measurements were made easy with the development of the Clark Polarographic sensor in 1956, the sensor works on the principle of electrochemistry. If a platinum cathode is maintained at a certain voltage with respect to a non-polarisable anode Leland et al. (1953) current flows between them when molecular oxygen is reduced at the platinum surface and the magnitude of this current depends upon the amount of oxygen reaching the platinum surface Kanwisher (1959). The smaller the exposed platinum surface, the smaller the current and more rapid the electrode's response to changes Leland et al. (1953). Electrochemical methods have several limitations: they consume oxygen, are influenced by sample flow rate, are affected by the presence of CO2 and H2S, and are susceptible to membrane fouling Trettnak et al. (1995). A steady-state electrochemical sensor consumes the oxygen it is measuring and is thus dependent on a flow past the sensor to obtain accurate measurements YSI (2017). Electrochemical DO measurements are affected by barometric pressure, temperature and the salinity, which should be measured and accounted for in the algorithm. Optical continuous sensing of oxygen is thought to have started in the 1930s. Optical sensing can be by spectroscopy, or by absorbtiometric probes which change colour when exposed to oxygen or by the widely used luminescent probes Wang and Wolfbeis (2014). Fluorescence measurements can be performed more rapidly and with greater sensitivity than absorption measurements Green and Blough (1994). The first fluorescent sensor system was described in 1968, Wang and Wolfbeis (2014) and Klimant et al. (1995) proposed the first reliable fibre optic oxygen sensors in 1995 specifically aimed at measuring oxygen in marine environments. Optical sensors are often referred to as optrodes and the functioning principle behind is that the analyte to be measured reacts with an indicator changing its optical properties which is then measured Klimant et al. (1995). In optrodes based on florescence these changes are in the form of changes in their florescence properties. The operation of the luminescence method is to emit a light with a specific wavelength which induces a luminescence in the sensing element. The chemical to be measured passes by the dye layer affecting the luminescence of the dye in both the intensity and lifetime, this is then registered by a photo-diode, YSI (2017). In the case of oxygen, it acts as a dynamic fluorescence quencher where it decreases the quantum yield of a flouropore, and thus this quenching of the flouropore can be used to measure oxygen contents McDonagh et al. (2001), Klimant et al. (1995). The accuracy

Electrochemical		Optical	
Advantages	Disadvantages	Advantages	Disadvantages
Fast response time	Frequent calibration required	Little calibration drift (months)	Slower response time
	Requires periodic maintenance (membrane replacement)	Less maintenance	
	Interference from gases such as H_2S	Not susceptible to interference	

Table 1. Advantages and disadvantages of Electrochemical and Optical sensors.

of the optical sensor is dependent on the temperature and thus the temperature must be measured and compensated for. According to YSI (2017) both electro-chemical and optical techniques measure with similar precision but the optical sensors have a slightly higher accuracy at concentrations from 0-20 mg/l. Until 2006 mostly electrochemical sensors were used in the industry, and some of the earliest optical sensors were applied in 2006, where in 2009 the first sub μ g/l sensors is launched for use in power plants Bell and Dunand (2010). The main advantages and disadvantages of the two primary DO measurements techniques, i.e. optical and electrochemical, have been listed in table 1.

2.1 Real Time Dissolved Oxygen Measurements for Feedback Control

The application of real-time DO measurements applied for feedback control of water injection deaeration has not been found. Several examples where low frequency daily samples are taken have been found in Alvis (1969), Carlberg et al. (1976), Byars et al. (1972). Dynamic real-time measurements have been performed as an example in Donham et al. (1991), where continuous DO concentrations are measured on an experimental test loop in the North Sea. Although this is a test setup, the measurements are used for evaluating dynamic changes in DO scavenger performance and not for feedback purposes. An analytical instrument manufacturer, Hach, claims that their optical DO sensor is applicable for DO measurements in offshore installations and specifically for injection water treatment. HACH (2017a), HACH (2017b). Nevertheless such applications have not yet been reported in the literature, although the importance of DO monitoring is clearly emphasized Hancock et al. (1988), Donham et al. (1991).

From a literature review it is evident that DO has been applied for monitoring and feedback control in various other industries such as municipal waste water treatment facilities, beverage industries and power-plants. In danish waste water treatment plants, DO measurements have been used for more than 30 years, Nielsen and Önnerth (1995), one such example is shown in figure 2. Several waste water treatment plants use on-line real-time ammonia measurements for feedback purposes, as ammonia directly determines the oxygen requirement in the activated sludge process, and rely on DO measurements for monitoring purposes Ingildsen et al. (2002), Yong et al. (2005). In Sheppard and Cooper (1990) chemostat control was achieved using a DO sensors for logic based feedback control, where the DO sensors were used to estimate the exhaustion of nutrients in the bio reactor. In Nguyen et al. (2000) a Mettler Toledo Ingold electrochemical DO probe was used for control of DO in a brewery waste water treatment facility. This system operates at a refresh rate of 20 minutes using a Self-Cycling Fermentation (SCF) control strategy which is based on a semi-continuous aerobic system and is based on a semi-continuous control strategy which controls the system in three stages. The DO measurements presented in this paper are based on extrapolated results from a strip recorder, thus analyses of the quality of DO results is difficult. Another example of a polarographic electrode DO sensors from Mettler Toeldo is in Wang et al. (2010), where it was applied for real time measurements of DO in broth in a bio-reactor. Direct applicability in the offshore water injection process of the methods above is difficult to determine without proper analysis, and as implementation of DO sensors in offshore installations is not common practice, several aspects must be considered.

2.2 Applicability of Dissolved Oxygen Measurements for Oil and Gas Activities

In the case of real-time measurements, on-line in-situ measurements are preferred as they have the benefit of measuring directly on the stream and thus receive a higher representation of the measured medium. Side stream in-situ monitoring can also be applied if direct in-line monitoring is not possible but this can introduce a change in state of the medium, Vojinović et al. (2006) and possible time delay, Durdevic et al. (2017). Fouling of sensors is one of the great concerns in offshore installations due to many impurities in the sea-water entering the system and due to the growth of microorganisms as mentioned earlier. The sensitivity of DO sensors towards fouling has been reported in waste water treatment in breweries, Nguyen et al. (2000), where fouling affected the feedback controller, and occasionally the probe was fouled to such an extent that the controller failed completely and a manual cleaning of the probe was done every 3-4 days. Although it is not the exact same environment, similar scenarios could occur, and fouling is known to affect the oil and gas installations, TUVNEL (2013) and Ebrahimi et al. (2010), which can cause drift in the measurements and thus decreased repeatability, Vojinović et al. (2006). Currently fouling of optical fluorescence equipment has been solved using free fall cells where the medium is not in contact with the optical window, Turner (2017), but the application of this technique to the optical DO sensors has not yet been found. Byars et al. (1972) lists several aspects to keep in mind, including calibration and temperature sensitivity. In addition, severely harsh conditions in the offshore oil and gas installations coupled with strict requirements for any new instrumentation that is installed are challenges which restrict new equipment from being installed. It is also a requirement that the equipment is low maintenance as this has large implications and costs due to the harsh conditions and due to inaccessibility of sensors. The operation of DO sensors in the offshore installations will vary depending on the application, and their real life performance is hard to determine before a full scale test has been carried out. Thus for any new equipment to be installed, a thorough testing must be done prior its installment.

3. DISSOLVED OXYGEN FEEDBACK CONTROL

In order to apply DO sensors to offshore oil and gas facilities for monitoring and feedback purposes, the following criteria must be satisfied:

(1) Real-Time measurements with an adequate sampling rate.
(2) On-line application, either in-line or as a side-stream with minimal delay.
(3) Manipulated variables

Current injection water treatment installations commonly rely on feed-forward type control strategies for removal of DO from the liquid, where the deaeration tower is operated at predefined vacuum, gas stripping and scavengers injections; according to daily off-line manual DO measurements. The most common real time feedback control is the level control of the bottom liquid in the deaerator, where the feedback parameter is the deaerator liquid level, which is not directly related to system performance i.e. DO concentration in the deaerator's liquid effluent. This can result in an over use of scavengers, stripping gas and energy for the deaeration process, which we believe could be improved if a reliable DO measurement was installed on the process line.

From other industries, such as the waste water industry, it is common practice to use DO as a feedback parameter for controlling DO. One such example is shown in figure 2, which is a plot of data collected from an aeration process at a Danish waste water treatment plant, Billund Vand A/S. The data represents an on-line DO measurement, the DO set-point which varies due to process requirements and the measured airflow into the sludge tank. The measured DO is used as a feedback parameter to control the air compressor, a simplified sketch of the process is shown in figure 3 We believe that a similar method could be applied to the offshore system, where the DO is measured and used as a feedback parameter in an advanced controller which controls the vacuum, nitrogen and the scavenger.

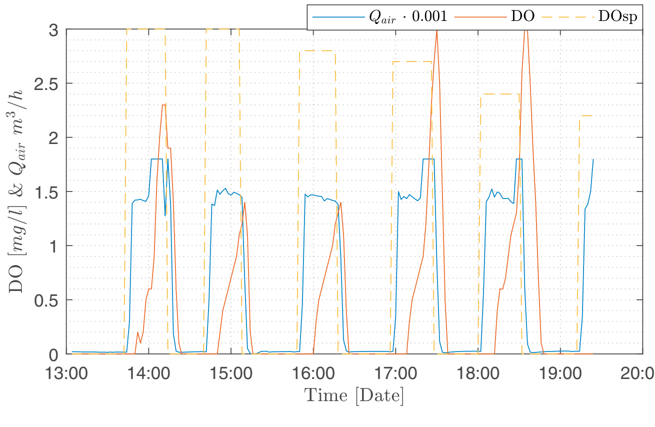

Fig. 2. DO control of a sludge tank in a waste water treatment plant.

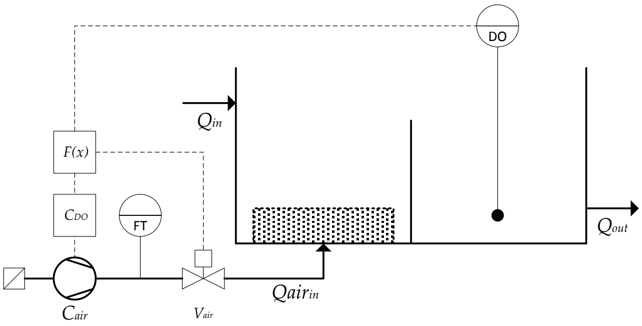

Fig. 3. Sketch of a waste water treatment plant sludge process dissolved oxygen control.

4. MODELING

This section proposes a potential model structure that could be applied for the deaeration process. Dissolved oxygen dynamics have been described in many works with respect to waste water treatment, referred to as activated sludge model or (ASM) for short, Henze et al. (1987), Gujer et al. (1995), Hess et al. (1996), Gujer et al. (1999), Henze et al. (1999), Henze et al. (2000), Henze et al. (2006), Holenda et al. (2008), Chai and Lie (2008), Han et al. (2012). In general, the ASM models describe absorption of oxygen and its consumption by biomass and the generation of biomass, these models were developed for waste water treatment plants (WWTPs). For the deaeration process a simplified version can be constructed which models the mass balance of DO as shown in equation 2, assuming that the mass inside the declaration column is well mixed.

$$\dot{y}(t) = D(t)(y_{in}(t) - y(t)) + K_{La}(u(t))(y_{sat} - y(t)) - R(t) \qquad (2)$$

Where $y(t)$ is the DO concentration, $D(t)$ is the dilution rate i.e. flow in $Q(t)$ divided by the total volume V, $(Q(t)/\text{V})$, K_{La} is the oxygen transfer rate which determines the diffusion of the dissolved gasses in the tower, Carlberg et al. (1976), y_{sat} is the DO saturation point and $R(t)$ is the respiration rate or the oxygen utilization rate by the microorganisms in the sludge, Carlsson et al. (1994). Determining the inlet DO concentration could be performed using DO measurements, analysis has shown that the DO has some variations $(2 - 4\%)$, at a depth of 50m in a period of a few months, but several challenges with sensor calibration and drift make this analysis questionable as the DO does not appear to follow the consistent changes in salinity and temperature, Emerson et al. (2002). As the residence time in a deaerator is short and the biocides are injected upstream the deaerator, the microbial life is considered negligible, thus the respiration rate $R(t)$ is can be omitted. The K_La remains unknown and it can be determined from parameter estimation based on experimental data.

The requirement for real-time DO measurements are further emphasized here if the diffusivity is to be estimated, however pilot scale measurements could be performed for model development and then these models can be used for estimator design on the platforms, which could be applied in advanced feedback control loops using e.g. LQG control or other Kalman based estimators.

As multi-stage deaerators are preferred due to their increased effectivity, the model can be expanded with a staged absorber model, Seborg et al. (2010), Durdevic et al. (2015). Assuming that we have a constant liquid holdup, no gas holdup, no mass change by the stripped gas at each stage, perfect mixing, the inlet is located at the top of the column and the vacuum pump is connected to each tray as shown in Hudgins Jr and Hanson (1971), then the gas concentration at each stage for a three stage deaerator can be represented by equation 3.

$$\begin{aligned} \dot{y}_1(t) &= D(t)(y_{in}(t) - y(t) - y_{out}) + K_{La}(u(t))(y_{sat} - y(t)) \\ \dot{y}_2(t) &= D(t)(y_1(t) - y(t) - y_{out}) + K_{La}(u(t))(y_{sat} - y(t)) \\ \dot{y}_3(t) &= D(t)(y_2(t) - y(t) - y_{out}) + K_{La}(u(t))(y_{sat} - y(t)) \end{aligned} \quad (3)$$

Where y_i is the DO concentration at stage i and the liquid flow from tray 1 through 3 is described by $D(t)$, i.e. $(Q(t)/\mathrm{V})$. This model will increases in complexity, for multiple vacuum outlets and with the addition of gas stripper. Further development of the model structure is required and eventually validation.

5. CONCLUSIONS

In the offshore Oil and Gas industry, keeping the dissolved oxygen (DO) concentration in the injection water low is of significant importance due to concerns regarding corrosion and the potential for fouling of the reservoir formations. Current water injection process have active DO scavenging applications which promise a low enough DO discharge, into the pipelines and reservoirs. But due to a lack of online and real-time measurements, continuous DO concentrations are unknown and variations could occur during the several daily sampling intervals. Control of the process, using DO as a feedback parameter, could reduce this effect and furthermore contribute to lowered energy consumption and reduce the use of scavenging chemicals. To enable continuous feedback control of DO, a reliable real-time measurement of DO must be available. Dissolved oxygen (DO) measurement techniques are abundant and are extensively used in other industries both for monitoring and feedback purposes. In most cases the DO measurements are applied to brewing,food, medical and waste water treatment operations, where the DO is either monitored to inspect the process or used for feedback control. So far no application of real-time DO measurements in the offshore water injection industry has been found.

More research needs to be applied in real time monitoring of DO in the offshore industry. This requires an extensive investigation of various DO monitoring techniques and equipment and their applicability in the offshore industry. As many commercial products are available, the applicability of those should be investigated as the initial step, and further possible upgrades to make them applicable. In addition, models of the deaeration process are equally important as they contribute to improvement of the precision of the measurements by applying online parameter estimation and facilitate the design of advanced control techniques. The development of a scaled pilot plant would facilitate the experimental analysis, model development and controller evaluation before real time implementation onto an oil and gas platform.

REFERENCES

Alvis, R. (1969). Comparison of waterflood corrosion detection and monitoring devices. *Material Protection*, 8(2).

Barnhart, M.C. (1995). An improved gas-stripping column for deoxygenating water. *Journal of the North American Benthological Society*, 14(2), 347–350.

Bell, S. and Dunand, F. (2010). A comparison of amperometric and optical dissolved oxygen sensors in power and industrial water applications at low oxygen levels ($< 5\ \mu\mathrm{g} \cdot kg^{-1}$). *Power Plant Chemistry*, 12(5), 296–303.

Bradley, H.B. (1987). Petroleum engineering handbook.

Brondel, D., Edwards, R., Hayman, A., Hill, D., Mehta, S., and Semerad, T. (1994). Corrosion in the oil industry. *Oilfield review*, 6(2), 4–18.

Byars, H., Gallop, B., et al. (1972). Injection water+ oxygen= corrosion and/or well plugging solids. In *SPE Symposium on Handling of Oilfield Water*. Society of Petroleum Engineers.

Cann, M. (2005). *Environmental chemistry*. Macmillan.

Carlberg, B. et al. (1976). Vacuum deaeration-a new unit operation for waterflood treating plants. In *SPE Annual Fall Technical Conference and Exhibition*. Society of Petroleum Engineers.

Carlsson, B., Lindberg, C.F., Hasselblad, S., and Xu, S. (1994). On-line estimation of the respiration rate and the oxygen transfer rate at kungsangen w astew ater treatment plant in uppsala. *Water Science and Technology*, 30(4), 255–263.

Chai, Q. and Lie, B. (2008). Predictive control of an intermittently aerated activated sludge process. In *American Control Conference, 2008*, 2209–2214.

Dake, L.P. (2001). *The practice of reservoir engineering (revised edition)*, volume 36. Elsevier.

Devold, H. (2013). *Oil and gas production handbook: an introduction to oil and gas production*. Lulu.

Dey, P.K., Ogunlana, S.O., and Naksuksakul, S. (2004). Risk-based maintenance model for offshore oil and gas pipelines: a case study. *Journal of Quality in Maintenance Engineering*, 10(3), 169–183.

Diaz, E., Gonzalez-Rodriguez, J., Martinez-Villafane, A., and Gaona-Tiburcio, C. (2010). H2s corrosion inhibition of an ultra high strength pipeline by carboxyethyl-imidazoline. *Journal of applied electrochemistry*, 40(9), 1633–1640.

Donham, J. et al. (1991). Offshore water injection system: Problems and solutions. In *Offshore Technology Conference*.

Durdevic, P., Pedersen, S., and Yang, Z. (2015). Modeling separation dynamics in a multi-tray bio-ethanol distillation column. In *Mechatronics and Automation (ICMA), 2015 IEEE International Conference on*, 1349–1354. IEEE.

Durdevic, P., Raju, C.S., Bram, M.V., Hansen, D.S., and Yang, Z. (2017). Dynamic oil-in-water concentration acquisition on a pilot-scaled offshore water-oil separation facility. *Sensors*, 17(1), 124.

Ebrahimi, M., Willershausen, D., Ashaghi, K.S., Engel, L., Placido, L., Mund, P., Bolduan, P., and Czermak, P. (2010). Investigations on the use of different ceramic membranes for efficient oil-field produced water treatment. *Desalination*, 250(3), 991–996.

Emerson, S., Stump, C., Johnson, B., and Karl, D.M. (2002). In situ determination of oxygen and nitrogen dynamics in the upper ocean. *Deep Sea Research Part I: Oceanographic Research Papers*, 49(5), 941–952.

Emmerson (2018). Reducing size in offshore topsides valve automation. http://www2.emersonprocess.com/en-US/brands/bettis/featuredSolutions/Pages/bettisSY.aspx. Online; accessed 19 Feb 2018.

Flammang, R.F., Medcalfe, T., Culligan, P.T., et al. (1976). Problems associated with the operation of offshore sea water injection systems. In *SPE European Spring Meeting*. Society of Petroleum Engineers.

Garcia, H.E. and Gordon, L.I. (1992). Oxygen solubility in seawater: Better fitting equations. *Limnology and oceanography*, 37(6), 1307–1312.

Green, S.A. and Blough, N.V. (1994). Optical absorption and fluorescence properties of chromophoric dissolved organic matter in natural waters. *Limnology and Oceanography*, 39(8), 1903–1916.

Gujer, W., Henze, M., Mino, T., Matsuo, T., Wentzel, M., and Marais, G. (1995). The activated sludge model no. 2: biological phosphorus removal. *Water Science and Technology*, 31(2), 1–11.

Gujer, W., Henze, M., Mino, T., and Van Loosdrecht, M. (1999). Activated sludge model no. 3. *Water Science and Technology*, 39(1), 183–193.

HACH (2017a). Accurate oxygen monitoring in meg injection solutions for closed-loop gas condensate pipelines application note. https://www.hach.com/orbisphere-k1100-ldo-sensor-kit-0-2000-ppb-410-controller-flow-chamber-wall-mount/product-downloads?id=12087715758. Online; accessed 26 April 2017.

HACH (2017b). Complete water analysis for the upstream oil & gas industry. https://www.hach.com/orbisphere-k1100-ldo-sensor-kit-0-2000-ppb-410-controller-flow-chamber-wall-mount/product-downloads?id=12087715758. Online; accessed 24 April 2017.

Han, H.G., Qiao, J.F., and Chen, Q.L. (2012). Model predictive control of dissolved oxygen concentration based on a self-organizing rbf neural network. *Control Engineering Practice*, 20(4), 465–476.

Hancock, W. et al. (1988). Operating experience and expansion of water injection facilities on the statfjord field to over 1 million bwpd. In *Offshore Technology Conference*.

Henriksen, N. (1985). Deaeration of water. US Patent 4,530,820.

Henze, M., Grady, C.L., Gujer, W., Marais, G., and Matsuo, T. (1987). A general model for single-sludge wastewater treatment systems. *Water Research*, 21(5), 505–515.

Henze, M., Gujer, W., Mino, T., Matsuo, T., Wentzel, M.C., vR Marais, G., and Van Loosdrecht, M.C. (1999). Activated sludge model no. 2d, asm2d. *Water Science and Technology*, 39(1), 165–182.

Henze, M., Gujer, W., Mino, T., and Van Loosdrecht, M. (2000). *Activated sludge models ASM1, ASM2, ASM2d and ASM3*. IWA publishing.

Henze, M., Harremoës, P., la Cour Jansen, J., and Arvin, E. (2006). Teoretisk spildevandsrensning: Biologiske og kemiske processer.

Hess, T., Chwirka, J., and Noble, A. (1996). Use of response surface modeling in pilot testing for design. *Environmental technology*, 17(11), 1205–1214.

Holenda, B., Domokos, E., Redey, A., and Fazakas, J. (2008). Dissolved oxygen control of the activated sludge wastewater treatment process using model predictive control. *Computers & Chemical Engineering*, 32(6), 1270–1278.

Holmager, M. (2010). Offshore book—an introduction to the off shore industry. *Esbjerg: Offshore Center Denmark*.

Hudgins Jr, C. and Hanson, R. (1971). How conoco floods with seawater. *The Oil and Gas Journal*, 69(7).

Hyne, N.J. (2012). *Nontechnical guide to petroleum geology, exploration, drilling, and production*. PennWell Books.

Ingildsen, P., Jeppsson, U., and Olsson, G. (2002). Dissolved oxygen controller based on on-line measurements of ammonium combining feed-forward and feedback. *Water Science and Technology*, 45(4-5), 453–460.

Kalvoda, R. (1984). Electrochemical analytical methods used in environmental analysis. *Science of the total environment*, 37(1), 3–7.

Kanwisher, John, W.H.O.I. (1959). Polarographic oxygen electrode.

Klimant, I., Meyer, V., and Kühl, M. (1995). Fiber-optic oxygen microsensors, a new tool in aquatic biology. *Limnology and Oceanography*, 40(6), 1159–1165.

Lee, J.S., Ray, R.I., Little, B.J., and Lemieux, E.J. (2005). Evaluation of deoxygenation as a corrosion control measure for ballast tanks. *Corrosion*, 61(12), 1173–1188.

Leland, c.C.J., Wolf, R., Granger, D., and Taylor, Z. (1953). Continuous recording of blood oxygen tensions by polarography. *Appi Phvsîol*, 6, 189–193.

Lyons, W.C. and Plisga, G.J. (2011). *Standard handbook of petroleum and natural gas engineering*. Gulf Professional Publishing.

McDonagh, C., Kolle, C., McEvoy, A., Dowling, D., Cafolla, A., Cullen, S., and MacCraith, B. (2001). Phase fluorometric dissolved oxygen sensor. *Sensors and Actuators B: Chemical*, 74(1–3), 124 – 130. doi: https://doi.org/10.1016/S0925-4005(00)00721-8. Proceedings of the 5th European Conference on Optical Chemical Sensors and Biosensors.

Nassivera, M., Essel, A., et al. (1979). Fateh field sea water injection-water treatment, corrosion, and scale control. In *Middle East Technical Conference and Exhibition*. Society of Petroleum Engineers.

Nguyen, A.L., Duff, S.J., and Sheppard, J.D. (2000). Application of feedback control based on dissolved oxygen to a fixed-film sequencing batch reactor for treatment of brewery wastewater. *Water environment research*, 72(1), 75–83.

Nielsen, M.K. and Önnerth, T.B. (1995). Improvement of a recirculating plant by introducing star control. *Water Science and Technology*, 31(2), 171–180.

Peel, J., Howarth, C., and Ramshaw, C. (1998). Process intensification: Higee seawater deaeration. *Chemical Engineering Research and Design*, 76(5), 585–593.

Popoola, L.T., Grema, A.S., Latinwo, G.K., Gutti, B., and Balogun, A.S. (2013). Corrosion problems during oil and gas production and its mitigation. *International Journal of Industrial Chemistry*, 4(1), 35.

Reis, D.J.C. (1996). *Environmental control in petroleum engineering.* Gulf Professional Publishing.

Robinson, D. (2010). Oil and gas: Water treatment in oil and gas production–does it matter? *Filtration & Separation*, 47(1), 14–18.

Seborg, D.E., Mellichamp, D.A., Edgar, T.F., and Doyle III, F.J. (2010). *Process dynamics and control.* John Wiley & Sons.

Sheppard, J.D. and Cooper, D.G. (1990). Development of computerized feedback control for the continuous phasing of bacillus subtilis. *Biotechnology and bioengineering*, 36(5), 539–545.

Skinner, D.R. (1982). *Introduction to petroleum production: well site facilities*, volume 3. Gulf Pub Co.

Skovhus, T.L., Enning, D., and Lee, J.S. (2017). *Microbiologically Influenced Corrosion in the Upstream Oil and Gas Industry.* CRC Press.

Trettnak, W., Gruber, W., Reininger, F., and Klimant, I. (1995). Recent progress in optical oxygen sensor instrumentation. *Sensors and Actuators B: Chemical*, 29(1), 219–225.

Turner (2017). Td-4100xd. https://oilinwatermonitors.com/portfolio-items/td-4100xd/. Online; accessed 26 April 2017.

TUVNEL (2013). Good Practica Guid - An Introduction to Produced Water Management. URL `http://www.tuvnel.com`.

Vojinović, V., Cabral, J., and Fonseca, L. (2006). Real-time bioprocess monitoring: Part i: In situ sensors. *Sensors and Actuators B: Chemical*, 114(2), 1083–1091.

Wang, X.d. and Wolfbeis, O.S. (2014). Optical methods for sensing and imaging oxygen: materials, spectroscopies and applications. *Chemical Society Reviews*, 43(10), 3666–3761.

Wang, Z.J., Wang, H.Y., Li, Y.L., Chu, J., Huang, M.Z., Zhuang, Y.P., and Zhang, S.L. (2010). Improved vitamin b 12 production by step-wise reduction of oxygen uptake rate under dissolved oxygen limiting level during fermentation process. *Bioresource technology*, 101(8), 2845–2852.

Wetzel, R.G. (2001). *Limnology: lake and river ecosystems.* Gulf Professional Publishing.

Willhite, G. (1986). Waterflooding, volume 3 of spe textbook series. *Society of Petroleum Engineers, Richardson, TX.*

Yong, M., Yongzhen, P., and Shuying, W. (2005). Feedforward-feedback control of dissolved oxygen concentration in a predenitrification system. *Bioprocess and biosystems engineering*, 27(4), 223–228.

YSI (2017). *The Dissolved Oxygen Handbook, a practical guide to dissolved oxygen measurements.*