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TITLE: POTENTIAL EFFECT OF THE TYPHOON VALVE, CASE STUDY OF OSEBERG C PLATFORM

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Abstract

Onshore and offshore facilities produce oil and gas worldwide. Globally, the daily oil production reached 83.6 million barrels per day in 2011. During the following years the production has continued increasing.

It was estimated that the amount of water produced were over 210 million barrels per day in 1999. Thereby averagely in a global aspect 3 barrels of water had to be produced per barrel of oil. In 2005, 67-72% of all oil produced was produced from mature fields, also called brown fields. These brown fields were believed to hold the majority of the oil resources and production capacity.

All produced water should be treated before it is discharged or re-injected to a reservoir. The level, of which the produced water has to be cleaned before discharge, depends on the regions environmental regulations. At the Norwegian continental shelf environmental regulations for discharged produced water are determined by the Norwegian Environmental Ministry and OSPAR. OSPAR has an average minimum demand that OiW (oil in water) concentration shall be less than 30 ppm in average, and a maximum discharge can be 49 ppm. The Norwegian Environmental Ministry has stricter environmental demands, requiring further reduction of both OiW and hazardous components.

Produced water treatment is usually carried out in different steps that use different enhanced separation techniques. Statoil ASA has an internal demand that a produced water treatment system shall always have two or more different separation enhancing techniques, to make it more resistant for system upsets. The most standard setup is to have hydrocyclones downstream the main separators that use enhanced gravitational separation and some kind of flotation unit downstream the hydrocyclones. A flotation unit increase separation by enhancing the density difference between oil and water.

Typhonix, a local company in the Stavanger region, has developed a low shear valve that has a positive effect on separation systems compared to standard valves. For the produced water, benefits by using typhoon valve have been observed to be a reduction of OiW. Other potential benefits are assumed to be reduction in WiO (water in oil), less need for production chemicals and generally better separation performance in downstream equipment.

Most of the typhoon valve test data has been obtained at laboratory conditions. In 2011 the valve was tested with real conditions and compared with a standard valve at Oseberg C. Positive results were also provided from the Oseberg C test.

In this report a case study of Oseberg C will be carried out. The objective will be to reveal if there will be overall benefits on the platform if all choke valves were replaced by typhoon valves. The study will be based on the typhoon valve pilot test at Oseberg C, other typhoon tests, theory about process units and consulting with process personnel from several oil companies. Some conclusions about the process system on Oseberg C have been made:

- The main gravity separators efficiency is increased when typhoon valve is installed compared to when a standard valve is installed. Increase in efficiency was observed as a reduction in OiW concentration by 55%.
- Hydrocyclone relative efficiency has been proven to be independent of feed OiW concentration as long as the droplet size is the same.
- Degasser relative efficiency has been proven to have some reduced performance when OiW concentration is reduced. The relative efficiency reduction increase when the amounts of OiW reduction increase.

A theoretical case study has been carried out on the platform to find what the total effect by changing standard valves with typhoon valves would be. This was done by using the knowledge obtained about the process system at Oseberg C and the reaction the system would have on an OiW reduction of 55%. The conclusions from the case study are:

- In this case a 55% reduction of OiW out of the separators will cause the OiW concentrations at the discharge point to be reduced by 55%. Causing oil discharged to sea to be reduced from 7.70 ton to 3.45 ton per year.
- The reduction of OiW out of the separator has the potential to reduce the amount of flocculants used by 55%, because flocculent dosing is dependent on OiW concentration. This reduction is equal to 36.7 – 110 ton of flocculent.
- The produced water system is believed to have a better buffering capacity for system upsets because the OiW concentration in the discharged water is generally lower.
- The positive effects from the typhoon valves are believed to be lowest at 50% water-cut. From valve tests conducted before this work, the benefits by applying a typhoon valve have increased when water-cuts were different from 50%. During the pilot test at Oseberg C the water-cut were close to 50%. Considering this, the typhoon valve is assumed to at least perform according to the results obtained in this work.

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1 INTRODUCTION

1.1 Process systems

When oil is located in the bedrock it is always located in a reservoir. A reservoir is a part of the bedrock with permeable rock with an impermeable layer on top called the reservoir trap (Selly 1998). Oil reservoirs often contain of water, oil and gas in layers. With water, the densest layer at the bottom and gas, the less dense layer at the top.

Offshore processing can be divided into two main processing areas, reservoir management and topside processing (Biker 2007). Drilling of wells, reservoir fracturing, chemical injection and flow control is important steps in reservoir management. Topside processing is where the production flow is separated.

Topside processing is divided into three treatment trains: gas train, oil train and produced water train (Ottøy 2013). The oil train separates oil, gas and water in two- and three-phase separators. As a result, clean and stable oil is produced in this process. Gas and water has to be treated further. Gas train is where gas is treated to reach the requirements for sales gas, or at least dry enough to make it suitable for transport and further treatment. When gas is separated from the liquids in the separators it is saturated with liquids. Drying of the gas is an important factor to prevent corrosion and formation of gas-hydrates in the transport system. The produced water train is where the water is treated to achieve required conditions for disposal over board or to be rejected.

As a field is being produced the oil layer in the reservoir is constantly drained (Ottøy 2013). At a certain point water will be produced together with the oil and gas. The produced water can have two origins. Formation water, which is the water layer naturally occurring in the reservoir. The other is injected water, which is water added into the reservoir to maintain pressure and thereby the production rates.

Since the first known commercial oil well was drilled in Oil Springs (Canada) in 1858 (lclmg.org). At this point oil production became a more reliable source of energy, because a higher production was achieved. Oil production rates have increased further, reaching 83.6 million barrels per day in 2011 and are still increasing (Energytrendsinsider.com).

As a field matures it produces more and more water. In 1999 it was estimated that for each barrel of oil, three barrels of water were produced (Khatib and Verbeek 2002). In 2005, 67–72% of all oil was estimated to be produced from mature fields, also called brown fields (Du et al. 2005). Brown fields should have a high focus, because the majority of oil resources and capacity lies within these fields.

At the Norwegian shelf the amount of brown fields are increasing. Some oil platforms are producing as much as 98% water (Ottøy 2013). The produced water has to be cleaned before it is re-injected into a reservoir or discharged to sea. It is common to discharge the produced water to sea at the Norwegian shelf. Even if the produced water is cleaned there are very high amounts of water produced. Thereby the total amount of emissions released together with the water will be high (KLIF.no b).

1.2 Environmental impact

Water production is increasing rapidly at the Norwegian shelf because most of the reservoirs which are producing have started to mature (KLIF.no b). Low concentrations of hazardous and radioactive components may be present in the produced water. So far there has not been observed any direct negative effect on vulnerable resources (KLIF.no a). More research will be carried out to find possible long-term effects which these components can inflict these resources. Re-injection of produced water is not necessarily a good solution for minimizing these hazardous components. Reinjection will probably not be demanded for fields with high water production, because the method is expensive and result in high amounts of CO_2 emissions.

1.3 Legal framework

In Norway all emissions are regulated by the Pollution Control Act, which is a legal framework for all pollution and waste. The main rule of the act states that pollution is forbidden, unless it is specially permitted by law, regulations or individual permits. KLIF (The Norwegian Pollution Control Authority) is a directorate governed by the Norwegian environmental ministry, and has the authority to issue discharge permits, require environmental monitoring and to demand hazardous chemicals to be phased out.

Several whitepapers (Stortingsmeldinger) has been released by the environmental authorities, setting targets for acceptable environmental pressure. In whitepaper Nr. 58 (1996-97) the zero environmental discharge strategy was introduced, were the goal was to have zero oil and hazardous chemical emissions to sea. All new fields have to be designed for the zero discharge objective from day one, while older installations had to initiate actions to reach the objective within 2005. Oil companies were also recommended to cooperate in evolving better technology for reinjection and cleaning produced water. The concept of the zero discharge strategy is to avoid damage to health and environment. Instead of waiting for the damage to happen before any actions are initiated. Trough whitepaper Nr. 26 (2006-2007) the government alerted that further actions were considered to achieve the goal of zero hazardous emissions in produced water.

In 2010 KLIF evaluated the achievements related to the zero discharge strategy. Hazardous chemicals added in production systems were reduced by 99% (KLIF.no b). Even if the goal of zero hazardous chemicals were not reached, the goal was assumed to be completed. The reduction of oil and natural occurring hazardous substances had been less than expected.
In the future KLIF will follow up the produced water quality and increase their efforts to reduce the oil and natural occurring hazardous substances released to sea.

The Norwegian technological strategy for the 21st century (OG21) has a main goal to make Norway keep the position as one of the cleanest oil and gas producing provinces worldwide (OG21 2012). One of the key objectives is to improve the produced water treatment to have a greater flexibility with regard to variations in flow rates, oil-water emulsions, solids and chemicals. Online monitoring of produced water and produced water reinjection are some of the main subjects in the strategy.

Oslo Paris convention (OSPAR convention) is an international convention that protects the North-East Atlantic marine environment. The OSPAR convention gives a minimum standard for the discharged produced water quality which the operator companies in the member states have to follow. If produced water is going to be discharged to sea, the OiW limit is 30 ppm (OSPAR recommendation 2001/1). Even if the minimum requirements for dispersed OiW are achieved, best available techniques (BAT) and best environmental practice (BEP) should be reviewed. In the OSPAR recommendation 2012/5 a risk based approach for produced water were introduced. This approach does not only consider OiW concentration, but also production chemicals and natural components. The requirement for each component depends on the effect it has on the environment.

1.4 Potential Typhoon valve benefits

Typhoon valve is designed to reduce the mixing of the components in the flow. This makes it suitable as a choke valve. If a choke valve or control valve is replaced with a typhoon valve, separation performance downstream the valve could be improved without the use of chemicals or additional methods. Potential benefits by applying the typhoon valve are:

- Less oil in water from the separator - less oil in discharged water
- Less water in oil from the separator – less water in exported oil
- Less liquid in the gas stream – dryer gas to the gas processing system
- Less need for, or improved effect of production chemicals
  - Emulsion breaker
  - Flocculants
  - Anti-foam

1.5 Master thesis objective

The objective of this work is to find what the effect would be if standard choke valves were replaced with typhoon valves at Oseberg C. Potential benefits will be presented as a comparison of the two types of valves. This will be associated with yearly release of oil with produced water, and yearly use of chemicals that are used to increase separation performance.

A theoretical case study of Oseberg C has been carried out. Oseberg C, operated by Statoil ASA has been chosen, because results from a field study with the typhoon valve have been available for further analysis.

1.6 Scope of work

The scope of this work is to evaluate the effect typhoon valve will have on the offshore produced water system at Oseberg C.

Yearly average values from the annual discharge report for the Oseberg field (Bratteteig & Dalsrud 2013), and average performance of the produced water system given by Statoil (Knudsen percom), will be used for calculating average values within the produced water system.

An important and demanding part of this work has been to conduct an extensive theoretical review of fluid characteristics, separation technology and separation systems. This was important to get enough knowledge and understanding of petroleum separation systems, to be able to predict how separation systems will respond to parameter alterations.

The effects that typhoon valve has on separator performance, has been used for calculating differences in average OiW values out of the separator for the two types of valves (Eidsmo et al. 2012). Average OiW reduction and values of relative performance based on oil concentration differences will be used for calculating the difference in performance between the two types of valves.

1.7 Layout of report

Chapter 1: Background for the report and the thesis objective.
Chapter 2: Summarizes the key definitions used in this work.
Chapter 3: Presentation of Oseberg field, Oseberg C and some typhoon test results.
Chapter 4: Explains the approach of the thesis.
Chapter 5: Is a theoretical review of fluid characteristics and separation technology.
Chapter 6: Comparison of standard valve and typhoon valve by calculations and discussion.
Chapter 7: The main conclusions

2 KEY DEFINITIONS

API gravity: American Petroleum Institute gravity, used to compare petroleum liquids with water.

EIF: Environmental Impact Factor

D_{50}: The average droplet size

Flooding chemical: is a type of chemical used in injected water, to increase the water viscosity. The water will then have preferable conditions when used as pressure support.

Footprint: Is used offshore to describe the amount of area equipment uses.

OiW: Oil in water, defined as the mass of oil in the water, normally given in ppm.

Operator: Is the oil company having the license to perform oil operations at a field.

Ppm: Parts per million, which is directly converted to mg/l or g/m^3.

Topside processes: Is referred to processes conducted at the platform above water level.

WiO: Water in oil, defined as the mass of water in the oil, normally given in ppm.

3 METHODS

The methods used in the theses include literature search, retrieve information from oil company personnel and obtain information about the process system at Oseberg C. This information was used to predict how the process system would react by using typhoon valve as choke valve.

3.1 Literature study

First of all, information about separation mechanisms had to be obtained. As a foundation for an overall understanding of the separation mechanisms, fluid characteristics and separation technology were studied. Experienced personnel from several oil companies have been consulted and information has been gathered from earlier research. This approach has been necessary to be able to understand how separation equipment is influenced by alterations in conditions.

Then information about the typhoon valve performance were obtained and studied (Eidsmo et al. 2012), (Husveg et al. 2009 a & b), (Husveg 2007). Knowledge about the typhoon valves effect compared to standard valves had been gained. Information about the process system at Oseberg C were gathered from the typhoon valve pilot test (Eidsmo et al. 2012) and by receiving information from Statoil personnel (Knudsen 2013), (Waage 2013), (Finborud 2013). Relative effects from the pilot test report were used as the main foundation for the study, because it is based on actual field data and tests carried out offshore at Oseberg C. But from this study only data from the effect of the separator were comparable for the typhoon valve and the standard valve. Relative efficiencies for the hydrocyclone and degasser had to be estimated by a reach study based on theoretical information and information given by consultants from oil companies. A substantial amount of effort has been used to obtain enough information about the separation equipment. This was necessary to be able to predict how the changes in the main gravity separator would affect the water treatment system.

Information given for the process system and comparison of the two systems (Oseberg C with standard valves and Oseberg C with typhoon valves) before this work, are summarized in Figure 1. Average reductions of OiW out from the separator were obtained from the typhoon pilot test (Eidsmo et al. 2012), while average values of OiW in the produced water outlet at Oseberg C were retrieved from the Oseberg field discharge report (Bratteteig & Dalsrud 2013). To find the average OiW at the gravity separator water outlet, average OiW of discharged produced water were used in addition to efficiencies of the hydrocyclone and degasser. Average separation performance for hydrocyclones and degasser were given by Statoil (Knudsen 2013).

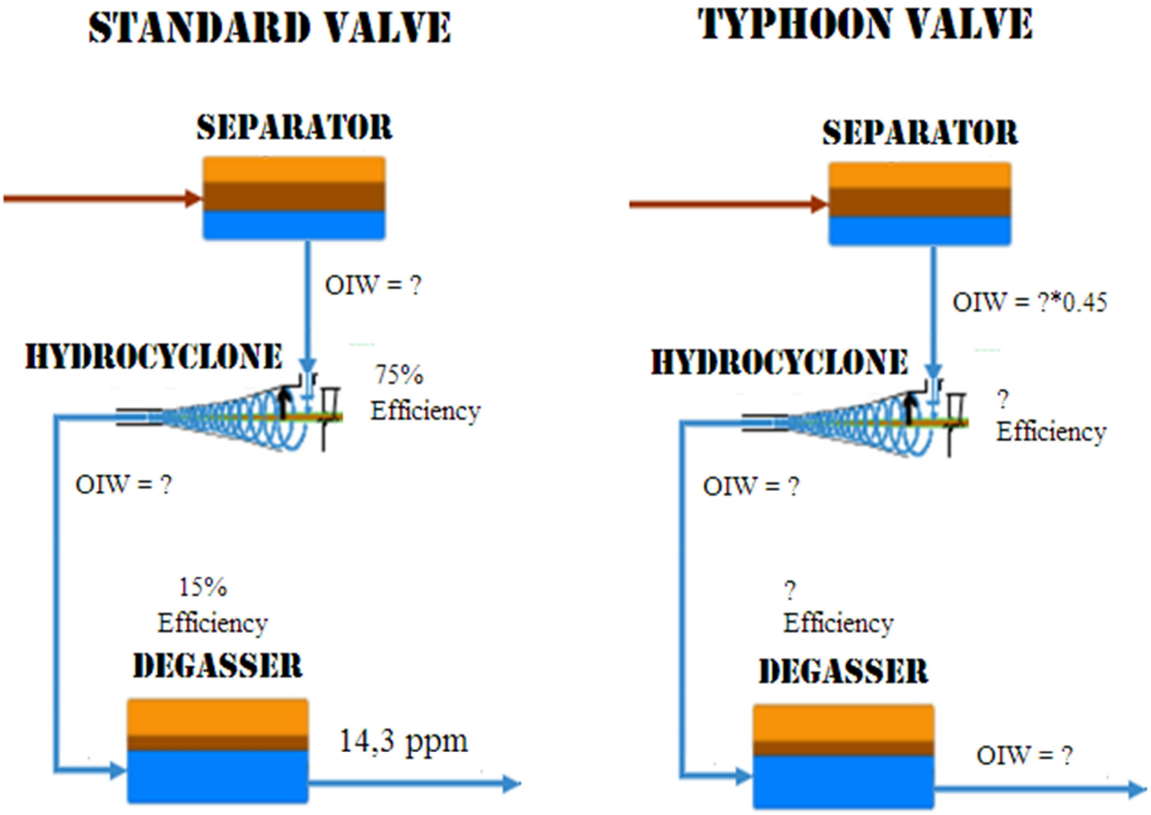

Figure 1. Information about the Oseberg C process system before the work started.

Average OiW values for the standard valve system were found by some easy percentage calculations. For the typhoon valve system the efficiencies of the separation system where not known.

To be able to find the typhoon valves separation system efficiencies, it was necessary to get an overall understanding of separation systems and the influence the condition changes between the systems would cause.

3.2 Consultants

Offshore processing is a big discipline where much of the knowledge is gained from experience. Therefore an important source for knowledge has been people with experience in the field. Statoil employees have been contacted trough the separation technology course. While employees at Cameron, Opus, M-I-Swaco, FMC, VWS Westgarth Ltd and Process Group has been approached by email.

4 THEORY

The important part of this chapter is to get an overall understanding of what is controlling the efficiency of equipment used in water treatment at Oseberg C. Oseberg C and some existing typhoon valve test results will be presented. To be able to get a good overall understanding of separation system performance it is important to start with a fundamental understanding. This chapter will start with a short introduction of the production flow composition, followed by fluid characteristics and chemicals effect. Fluid characteristics and content of the production flow is important to understand separation technology, which will be the next part of this chapter. At the end of this chapter process equipment used in oil and water separation system at Oseberg C will be reviewed.

4.1 Typhoon valve and Oseberg field study

4.1.1 Oseberg field

Oseberg is an oil and gas producing field, producing from a sandstone reservoir (Ramstad et al. 2012). The field is established approximately 130 km west from Bergen, and has an average sea depth at about 100m (Statoil.no a), (Ramstad et al. 2012). In 1988 Oseberg B platform initiated the first production at the Oseberg field.

All oil and gas produced at the field is transported through the transport system at Oseberg Field Center (Ramstad et al. 2012). Oil produced is transported to Stureterminalen, while produced gas is either re-injected or transported to the Heimdal field. From there the gas is transported with the Statpipe-system to Britain. A summary of the field’s installations and relative locations is shown in Figure 2.

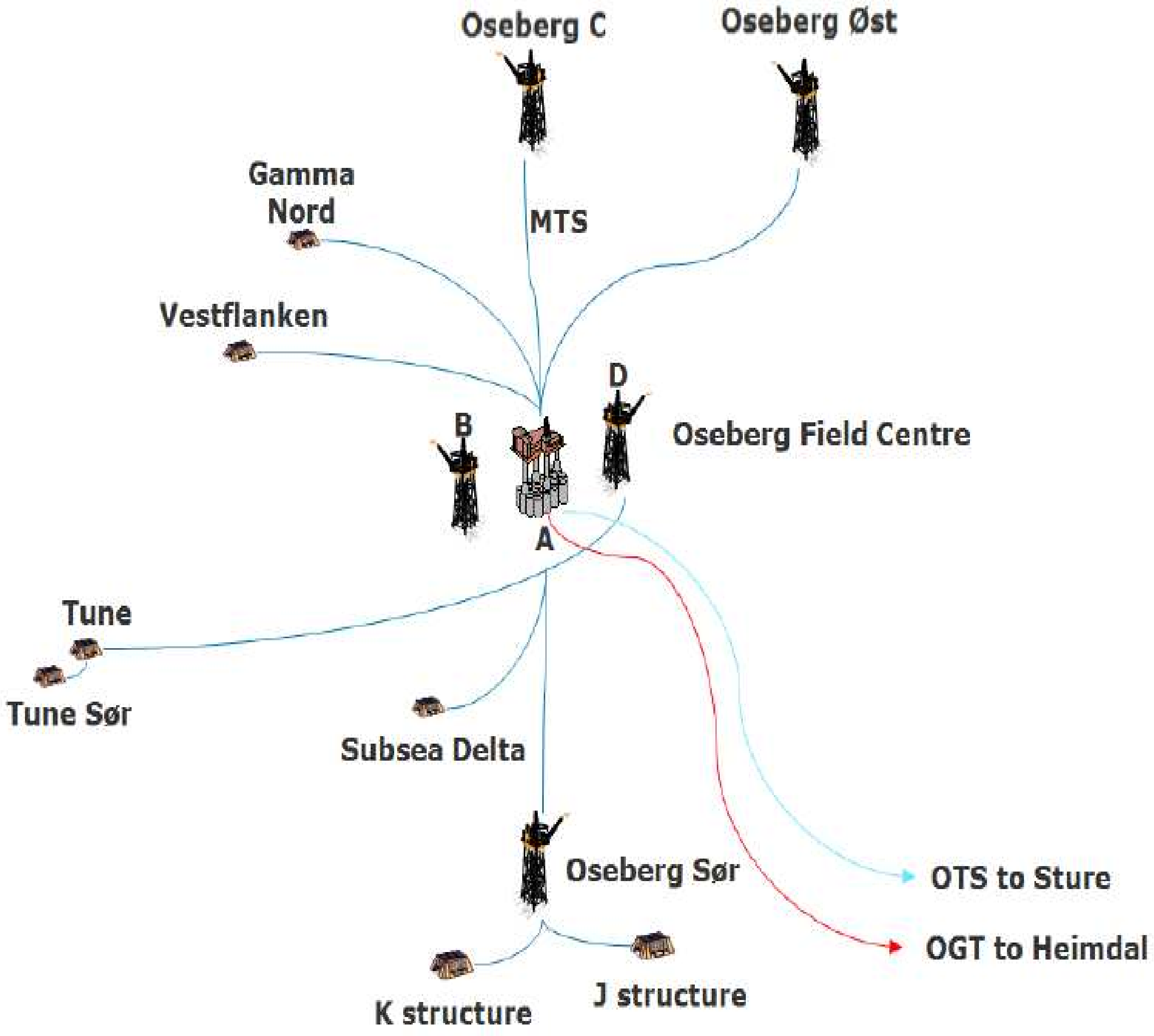

Figure 2. Overview Oseberg field (Ramstad et al. 2012).

4.1.2 Oseberg C

Oseberg C (Figure 3) is an oil rig at the Oseberg field that started production in 1991 (Statoil.no b). The rig is located 10 km north of the Oseberg field Center. There are 15 oil producing wells producing to Oseberg C, and three oil wells that are routed directly to Oseberg Field Center without being processed. Daily this oil rig produces 3000 m^3 of oil and 2000m^3 of water, yielding 40% water cut. Processed oil is transported to Oseberg Field Center and the produced gas is used for reservoir pressure maintenance. Three sea water injection wells and 5 gas injection wells are used for pressure support at Oseberg C.

Figure 3. Oseberg C (offshore.no)

4.1.2.1 Oseberg C produced water system

An overview of the process system is displayed in Figure 4 (Knudsen 2013). Each production well has a choke which reduces the pressure and flow before the production fluids are roughly separated in the two parallel first stage separators. These are the main separator (1) and test separator (2). The oil stream is directed to the second stage separator (3). Further downstream in the oil "train" there is a horizontal oil-gas separator (4) operated at atmospheric conditions to release gas from the oil which stabilize it before transportation. The last stage of the oil "train" is an oil-water horizontal gravity separator (5) separating out some more water before transportation. The water from the water-oil separator is re-injected into the three-phase flow before the second stage separator.

Produced water from the first and second stage separators are first treated by de-oiling hydrocyclones (6) before the last stage of the produced water "train" which is a degasser (7). Flocculants are injected upstream the hydrocyclones. Oil from the degasser is further treated in an oil spill tank (8). Oil from the spill tank and from the reject-flow from the hydrocyclones is re-injected into the production flow in front of the second stage gravity separator.

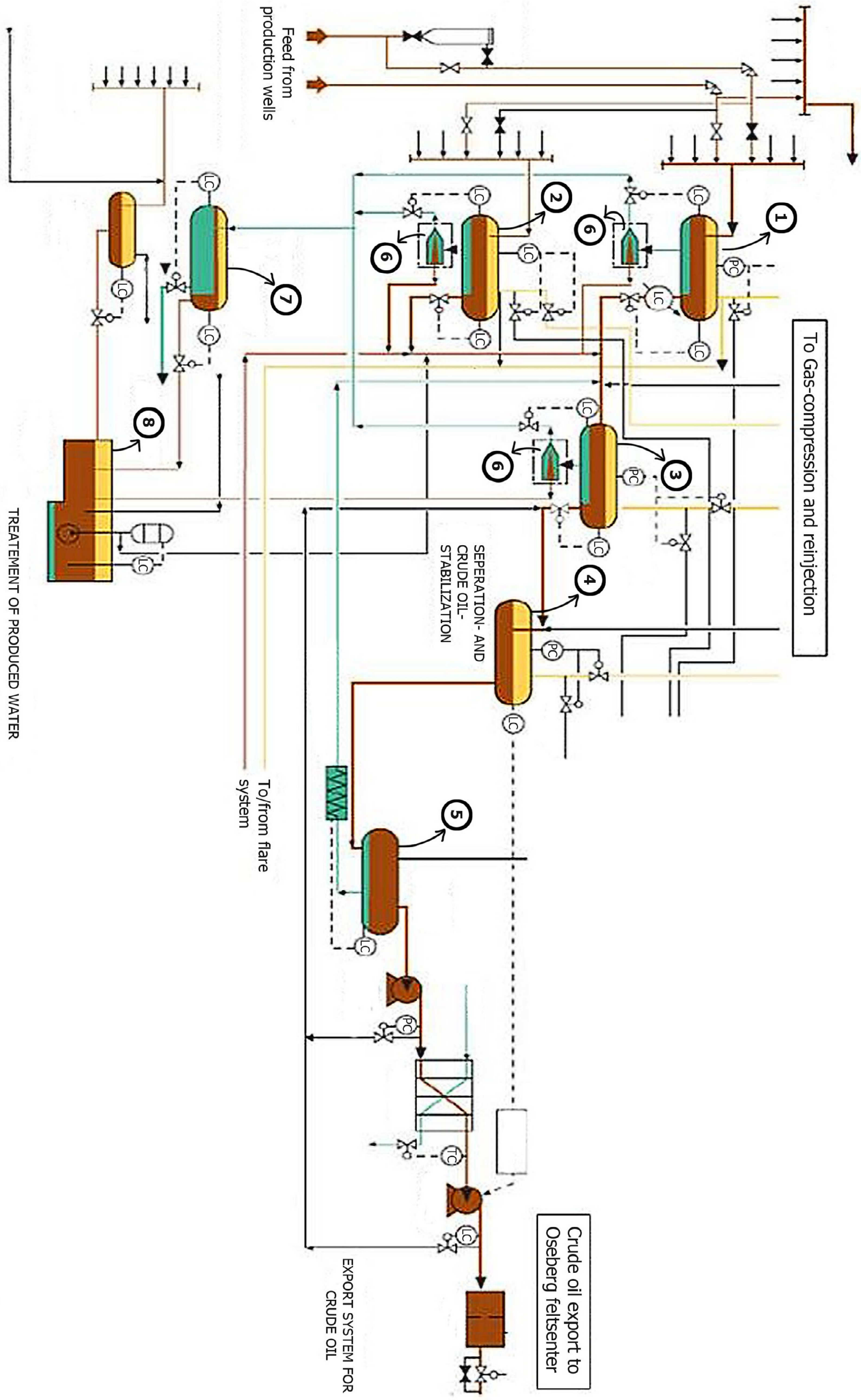

Figure 4. An overview of the process system at Oseberg C (Knudsen 2013).

4.1.3 Typhoon valve tests

To describe the typhoon valve advantages, a short review of the pilot test and the prototype test will be presented.

4.1.3.1 Oseberg C pilot test

A typhoon pilot test was conducted at Oseberg C, operated by Statoil (Eidsmo et al. 2012). As a pre-study, several wells were studied to determine which would be the best to demonstrate the typhoon valve characteristics and benefits. Well C-03 were chosen because of high water cut (75%) during the last well test, which is believed to be one of the water cuts where the typhoon valve is most beneficial (Husveg et al. 2009 a).

The test program conditions included (Eidsmo et al. 2012):

- Normal conditions with 10 ppm emulsion breaker
- Reduced emulsion breaker to 5 ppm
- Reduced separator water level (from approximately 13 to 9 minutes retention time)
- Reduced separator oil level (from approximately 15 to 8 minutes retention time)
- Reduced production rates (to increase the pressure reduction across the valve) with 20 ppm emulsion breaker.

There were sampling points for oil and water analysis upstream and downstream of the valve in addition to the oil and water outlets from the separator.

During testing, the well produced at approximately 50% water cut, which is believed to be a difficult area of separation (Choi 1990). Even under these conditions the average reduction in the OiW concentrations at the separator outlet were 55% when operating with typhoon valve compared to the standard valve (Eidsmo et al. 2012). Improvements were also observed with regard to WiO concentrations at the oil outlet of the separator. Overall the average reduction of WiO was 35%. However, this positive effect was variable and non-conclusive.

Figure 5. Typhoon valve pilot test (Typhonix).

4.1.3.2 Porsgrunn prototype test

The prototype test was executed at Statoil's test facility at Porsgrunn, where real size valves were tested (Husveg et al. 2009 b). Realistic conditions were used for temperature, pressure, flow and fluid conditions. Also the valves were tested at a wide range of water cuts. Standard and typhoon valve were installed in parallel, as shown in Figure 6, upstream a pipe separator which was operated with only a few seconds retention time. The main focus of this study was the OiW concentration at the pipe separator outlet.

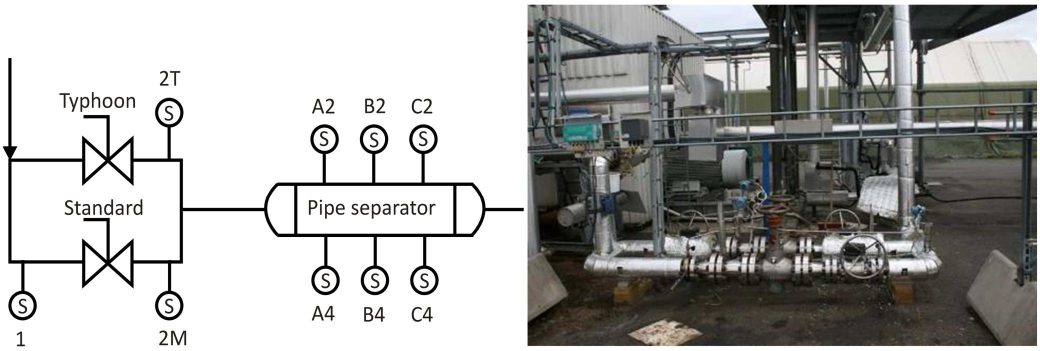

Figure 6. Prototype testing at Statoil's multiphase flow loop in Porsgrunn (Husveg 2009 b).

The range of conditions the valves were (Husveg et al. 2009 b):

- Tested was water cuts from 10-90%
- Pressure drop over chock valve from 4 to 10 bars
- Gas/liquid ratios from 0.1 to 0.5.

Based on average values an increase in the relative performance of typhoon valve compared to the standard valve was observed as the water cut increased. Even though, there were significant deviations for both valves at 80 and 90% water cut. Lower WiO values were also observed when operating the typhoon valve. But mostly these values were low and non-systematic.

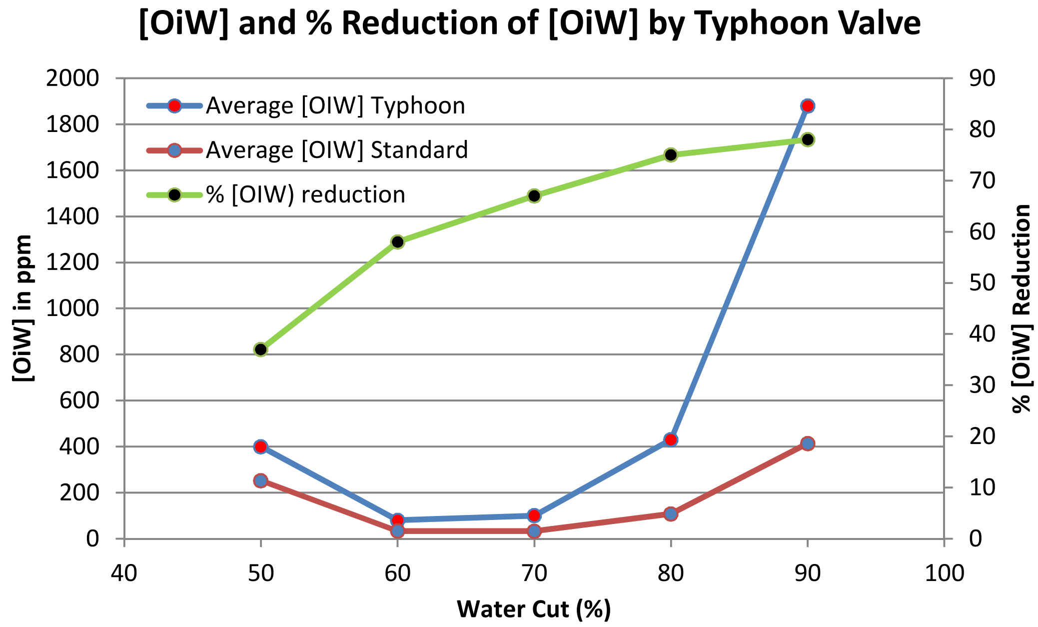

Figure 7. Results from Porsgrunn prototype test (Husveg et al. 2009)

4.2 Production fluid composition

4.2.1 Crude oil

Crude oil can have a diversity of components such as alkanes, cycloalkanes, aromatics and asphaltens (Selly 1998). Oil density is determined by molecular size and the quantities of the different components. American Petroleum Institute gravity (API gravity) is a standard measurement for comparing oil containing liquids to water. API values higher than 10 indicates that water is denser than the liquid. When the API value is lower than 10 the liquid is denser than water. The closer the density of the liquids are, the harder they are to separate.

4.2.2 Gas

Produced gas contains components as methane, ethane, propane and butane (Selly 1998). Also heavier gases can be a part of the gas phase, but will take the form of condensate during the gas process train because of an increase in pressure (Ottøy 2013). There are several gas definitions, depending on the gas conditions, like, LNG (Liquefied natural gas), NGL (Natural gas liquids), LPG (liquid petroleum gases), Wet gas, Rich gas, Dry gas and Sales gas.

4.2.3 Produced water

Produced water is the main waste stream in oil and gas production (Finborud 2013). The content of the produced water depends on the reservoir conditions, chemicals used and upstream processes (Ottøy percom), (Waage 2013). Common content is dissolved gas, dissolved minerals, dissolved organics, suspended solids and suspended oil.

As an oilfield gets mature, it produces more water, and the cost of producing water is often considered a burden (Frankiewicz et al 2012). But produced water also has a value. Allowing water to be produced increases the amount of oil which can be recovered from a reservoir. By improving the produced water facility both oil recovery and cost of well work-over can be reduced (Mohammad et al. 2011). With the increasing oil prizes it can be beneficial to produce oil from wells that have up to as high as 98 % water cut (Magnar Septec).

Produced water can be minimized with mechanical and/or chemical treatment (Waage 2013). Mechanical treatment can be plugging of the section of the well which is within the water-column. While chemical treatment can be performed by introducing chemicals that reduce water flow.

4.3 Fluids characteristics

Fluid characteristics give a fundamental understanding of how of how fluids interact, and is therefore important to understand why separation occurs. Density, viscosity, interfacial tension and how chemicals can affect these parameters are reviewed.

4.3.1 Density

Density is defined as mass per volume at standard conditions (4.1). Gas density depends a lot on conditions like pressure and temperature (Finnemore & Franzini 2002). These conditions have less influence on liquids and solids.

$$\rho = \frac{m}{V} \tag{4.1}$$

Oil density is often given in API gravity which is explained by equation 4.2 (Selly 1998).

$$API\ gravity = \frac{141{,}5}{SG} - 131{,}5 \tag{4.2}$$

SG = Standard gravity

Standard gravity can be calculated when you have API gravity by a modification of equation 4.2, which result in equation 4.3

$$SG = \frac{141.5}{API\ gravity + 131.5} \tag{4.3}$$

The salinity of the produced water can change from field to field. Gas producing fields usually has close to zero percent salinity, while oilfields usually have salinity between 2 and 15 percent (Finborud 2013). The most common ions in produced water are sodium, potassium, calcium and chloride. Salinity is often given in percent or ppm, were one percent counts for 10 000 ppm. The salinity influences the water density. At zero percent salinity the density of water is approximately 1000 gram per liter at 15 °C, while if the salinity is 15 percent the density of water is approximately 1010 gram per liter at 15 °C (Figure 8).

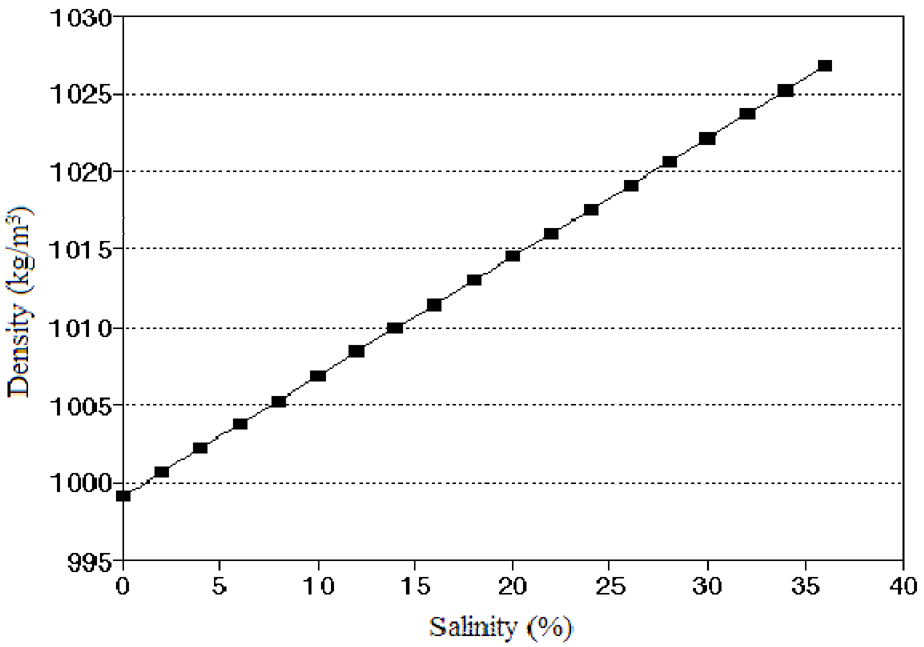

Figure 8. Salt influence on water density (Marietta.edu).

In process chemistry the relative density is most important, because conditions can be quite different in different processes (Ottøy 2013). In a first, second and third stage separator the pressure decrease rapidly. This gives different separation conditions in the different separators because lighter components are converted to gas. If oil has a similar density to water, emulsions are very hard to separate. Water salinity has a direct influence on the water density. Increasing salinity therefore usually increases the oil-water separation.

4.3.2 Viscosity

Viscosity is a measure of the “thickness” in a liquid. High viscosity is caused by high resistance between molecules and results in a more solid-like liquid. The correlation between shear stress, force, area, viscosity and velocity gradient is given in equation 4.4 (Finnemore & Franzini 2002).

$$\tau = \frac{F}{A} = \mu \frac{\partial u}{\partial y} \qquad (4.4)$$

Ƭ = Shear stress
F = Force
A = Area
µ = Dynamic viscosity
$\frac{\partial u}{\partial y}$ = Velocity gradient

The viscosity of continues phase are of great importance in separation technology (Finnamore & Franzini 2002), (Ottøy 2013). If the viscosity is increased, the dispersed phase will be retained in continues phase longer. Viscosity of the dispersed phase has lower importance. Water viscosity is usually quite constant, while oil viscosity is highly influenced by temperature.

4.3.3 Interfacial tension

Interfacial tension is a measurement of free energy at an interface, for example liquid-liquid, gas-liquid, gas-solid and liquid-solid (Biolin Scientific AS). It is often measured in the amount of energy required to increase the surface area, which is a measurement of energy/area. This force can also be explained by a force/length measurement (mN/m or dynes/cm). Interfacial tension can be used to explain why suspended droplets and bubbles tend to have a spherical configuration, because the spherical form has the lowest area per volume ratio.

Interfacial tension can be increased by for example corrosion inhibitor or other kinds of production chemicals. An increase of interfacial tension reduces the amounts of droplet brake up that occur, but makes the droplets more stable (equation 4.12), (Finborud et al. 1999).

4.3.4 Zeta potential and double layer theory

The zeta potential has it origin from the double layer theory (Barnes & Gentle 2005). This theory states that there are two layers surrounding a suspended phase in a liquid. The phase surface has a positive or negative electric potential, and is coated with ions of the opposite electric potential. Outer layer is a defuse layer of ions with an opposite electric potential then the inner layer. Zeta potential refers to the difference in electric potential between the inner and the outer layer (Figure 9).

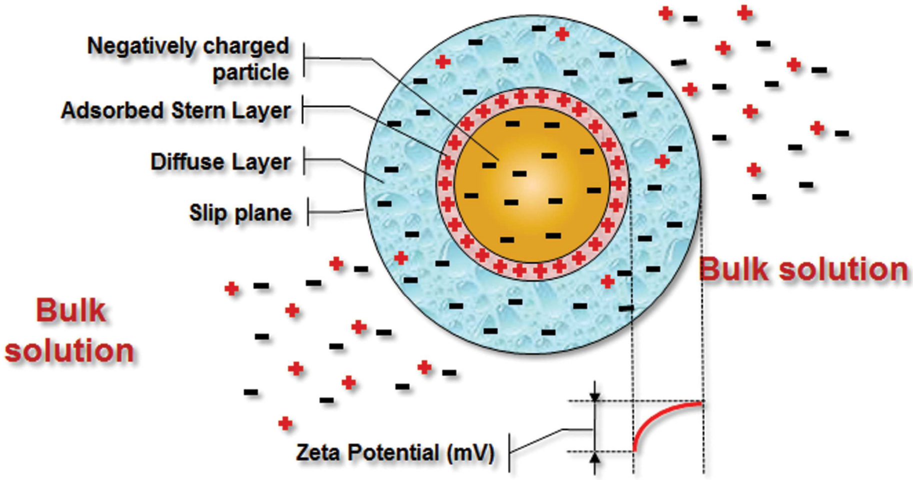

Figure 9. Illustration of zeta potential (DrillingContractor.org).

A high zeta value makes emulsions stable because droplets tends to repel each other (Finborud et al. 1999). Salts in the solution increase the electric potential of the outer layer and derby reduces the stability of the emulsion, as viewed in Figure 10.

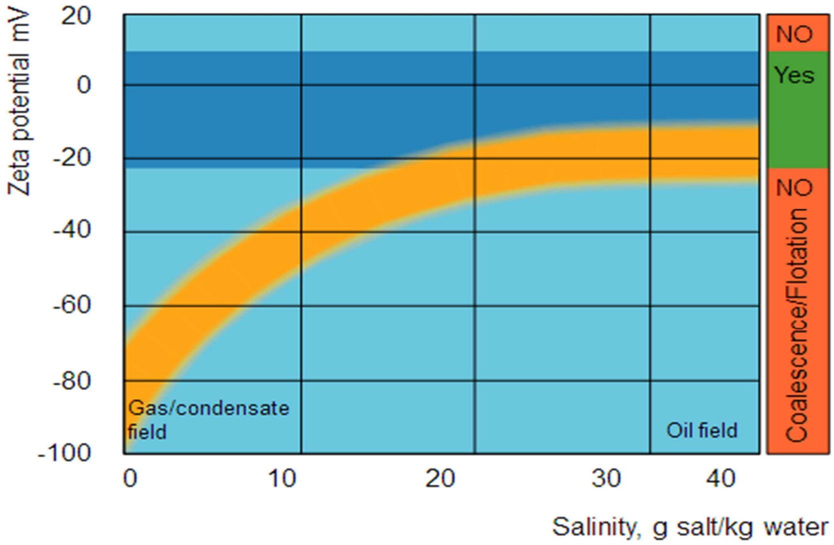

Figure 10. Droplet coalescence as a function of water salinity (Finborud et al. 1999)

4.3.5 Production chemicals

There is a wide range of production chemicals used in oil and gas production. Some groups of chemicals are corrosion inhibitors, scale inhibitors, hydrate inhibitors, flocculants, emulsion breakers, wax inhibitors, anti-foam chemicals and drag reducer (Waage 2013). These chemicals are used in the process for different beneficial purposes. Corrosion inhibitors reduce the amount of corrosion which increase the production safety and reduce the amount of maintenance needed inside pipes and process equipment.

Corrosion inhibitors are surface-chemicals and can interfere with oil-water separation by stabilizing emulsions (Hustad et al. 2011). Other surface active chemicals are scale inhibitors, hydrate inhibitors and wax inhibitors. Emulsion breakers and flocculants are chemicals used to increase separation and reduce the negative effect of other production-chemicals.

4.3.5.1 Flocculants

Flocculants are water solvable chemicals which are added to production-flow to increase the separation of oil dispersions from the water phase. There is a maximal effective dosage for each concentration of oil-droplets (Figure 11), (Finborud 2013), (Waage 2013). Optimal dosing is when as much as possible of the flocculent is used to flocculate oil droplets, and as little as possible of the flocculent exits with the produced water. Efficiency of the chemical, efficient mixing and dosing control is important to achieve optimal dosing.

The OiW concentration changes frequently at a process facility (Finborud 2013), (Waage 2013). Therefor it is normal to use a standard dosage with some fine-tuning. Standard flocculent dosing can be 7.5 ppm based on water production (Kroknes 2011).

Multiple injections of flocculants are preferable in the produced water system to increase the effectiveness of the chemicals (Waage 2013), (Finborud 2013). Sadly most facilities only have one injection point, normally in front of the hydrocyclones downstream main gravity-separators.

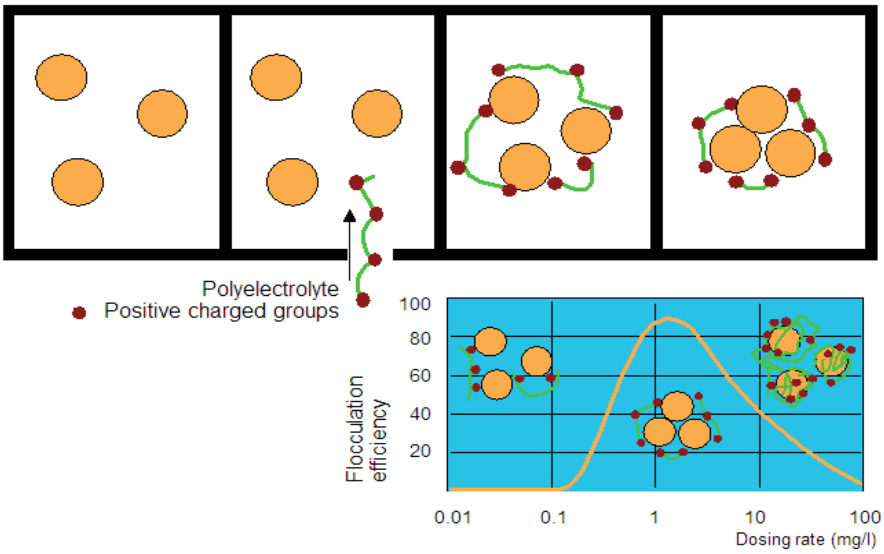

Figure 11. Flocculent efficiency curve (Finborud 2013).

The optimal dose of flocculent needed is most likely to change proportional to the fraction of OiW reduction (Waage persmed), (Finborud persmed). To find the reduction of flocculent when OiW is reduced, equation 4.5 can be used.

$$F_r = F_a \cdot \frac{OiW_T}{OiW_S} \qquad (4.5)$$

F_r = Reduction of flocculent needed
F_a = Amount of flocculent used in 2011
OiW_T = oil concentration at the separator water outlet when using typhoon valve
OiW_S = oil concentration at the separator water outlet when using standard valve

4.3.5.2 Emulsion Breaker

Emulsion breakers dissolve in oil, where it migrates to the oil/water interface and weaken the stable film that inhibits the water droplets to interact (Choi 1990). The chemical can be injected before the separator to increase coalescence of water droplets, which enhances the separation efficiency. Standard dosing of emulsion breakers are typically 2.5 ppm based on the total production (Kroknes 2011).

With changes in the properties of the production-flow the emulsion breaker can have high reduction in efficiency (Waage 2013). A chemical that works at one field does not necessarily have any effect on another field. The understanding of exactly how an emulsion breaker works is not yet agreed upon.

4.4 Separation

Oil-water separation has been considered to be the most common and least understood process in the petroleum production facility (Arnold & Koszela 1990). This chapter describes how separation is affected by alterations in fluid characteristics, gravitational forces and emulsions, and how Stokes law can be used to optimize separation.

4.4.1 Stokes law

Stokes law can be used to predict velocity of a bobble, droplet or particle in a fluid by gravity separation (equation 4.6), (Finnemore & Franzini 2002). Gravity separation is driven by density differences between the continuous and the dispersed phase, and can be applied to estimate the velocity in both sedimentation and flotation. But it can only be used for ideal conditions. Ideal conditions include no droplet-droplet interactions, laminar flow (Reynolds number < 1) and that only spherical particles/droplets are considered. Even if the conditions in separation equipment differ from ideal conditions, Stokes law is often used for basic fundamental understanding in petroleum separation technology (Ottøy 2013).

$$V_s = \frac{gD^2 * (\rho_1 - \rho_2)}{18\mu} \tag{4.6}$$

V_s = Settling velocity
ρ_1 = density of continuous phase (kg/m^3)
ρ_2 = density of dispersed phase (kg/m^3)
μ = Fluid viscosity
g = constant for gravitational acceleration (m/s^2)
D = droplet diameter (m)
μ = Dynamic viscosity of continuous phase (kg/(m/s))

By referring to Stokes law it is possible to determine possible approaches to manipulate more efficient separation efficiency (Ottøy 2013). Modifying the acceleration, viscosity and/or droplet size are common methods to increase separation performance. Viscosity can be changed by heating the fluids while chemicals and/or mechanical components can be used to increase droplet size. The droplet size of the dispersed phase is the parameter which has the most significant effect on settling velocity.

In a centripetal unit the droplets in the fluid is exposed to a centripetal acceleration which can be explained by equation 4.7 (Husveg 2007).

$$a_c = \omega^2 * r = \frac{V_T^2}{r} \qquad (4.7)$$

a_c = Centripetal acceleration (m/s^2)
ω = Angular velocity (s^{-1})
r = radius (distance from cyclone centre) (m)
V_T = tangential velocity (m/s)

The angular velocity in a centrifugal unit can be given by equation 4.8.

$$\omega = \frac{V_T}{r} = \frac{\frac{n*2*\pi*r}{60}}{r} = \frac{n*2*\pi}{60} \left[\frac{m}{s^2}\right] \qquad (4.8)$$

n = number of revolutions per 60 seconds

By replacing the gravity constant with the centripetal acceleration (4.7) in Stokes law (4.6), the equation can be used to determine the settling velocity in centripetal units (4.9).

$$V_s = \frac{V_T^2 * D^2 * (\rho_1 - \rho_2)}{18 * \mu * r} \qquad (4.9)$$

4.4.2 Emulsions

An emulsion is a mixture of liquids which normally are immiscible, i.e. oil and water. Emulsions can have various concentration of dispersed phase. With high concentration of dispersed phase the viscosity of the mixture can increase (Choi 1990). Dispersions typically build up at the oil water interphase in gravity separators. Droplet breakup (dispersion) and coalescence are the most important processes during emulsification (Lobo and Svereika 2003).

Inorganic scales, asphaltenes and high amounts of shearing seem to increase the stability of the emulsions in oil-water separation (Kokal et al. 2000), (Lobo & Svereika 2003). Problems regarding emulsion are slower separation, more water in oil and more oil in the produced water. High temperature has been found to reduce emulsion problems (Kokal et al. 2000), (Al-Ghamdi et al. 2003). While Nguyen et al. (2011) found trends that indicated a reduction in emulsion stability with increased salinity and decreased temperature. Al-Ghamdi et al. (2009) concluded that density, viscosity, solid content and TDS could be used to estimate the tightness of the emulsion. Kokal et al. (2000) developed a method to diagnose and treat emulsions. This method was also supposed to help with emulsion breaker selection. Equipment used for emulsion treatment usually combine chemical and physical treatment (Bensadok et al. 2007). Metal salts, acids and synthetic polyelectrolytes can be used to destabilize the emulsions to increase agglomeration.

4.4.2.1 Dispersion

Dispersion can occur under several conditions where turbulence of some kind has to be present. In petroleum production dispersion is common in piping, valves and other process equipment. Choke valves in relation to oil dispersion is considered to be a critical point for the amount of dispersions in petroleum production. Therefore choke valves has been studied several times over the last years (van der Zande et al. 1998), (van der Zande 2000), (Muntinga 1998), (Husveg et al. 2007), (Husveg et al. 2009), (Husveg 2007).

Energy dispersion is an important factor in droplet breakup and can be estimated by using equation 4.10 (Finnemore & Franzini 2002).

$$\varepsilon = \frac{\Delta P * Q}{\rho * V_{DIS}} \tag{4.10}$$

ε = Energy dissipation
ΔP = Pressure drop across orifices
Q = mean fluid velocity
V_{DIS} = Volume where energy dissipation takes place
ρ = density

The Weber number (We) is a dimensionless number describing the ratio between disturbing and restoring stress on a droplet, and can be used to describe the forces affecting a droplet (equation 4.11), (van der Zande et al. 1998).

$$We = \frac{\rho \cdot \varepsilon^{2/3} \cdot d^{2/3}}{\sigma} \tag{4.11}$$

σ = Interfacial stress (N/m)

Hinze's theory can be used to find the largest stable droplet size (d_{max}) in a turbulent system where μ is negligible (4.12) (van der Zande et al. 1998).

$$d_{max} = We_{crit}{}^{3/5} \cdot (\frac{\sigma}{\rho})^{3/5} \cdot \varepsilon^{-2/5} \tag{4.12}$$

For systems where viscosity cannot be ignored van der Zande (2000) concluded that equation 4.13 could be used to find the largest stable droplet size.

$$d_{max} = C \cdot (\frac{4\sigma \cdot \mu_d \cdot u_{in}}{\rho_c})^{3/5} \cdot \varepsilon^{-2/5} \qquad [\mathrm{m}] \tag{4.13}$$

μ_d = viscosity of the dispersed phase (Pa*s)
u_{in} = characteristic velocity inside a droplet (m/s)
C = constant of proportionality
ρ_c = density of continues phase

4.4.2.2 Coalescence

Coalescence is the process where two or more droplets collide and form one bigger droplet. When two dispersed droplets of the same phase collide, it does not necessarily cause them to coalesce (Finborud et al. 1999). Oil droplets usually have surfactants or particles at the surface which stabilizes and give the surface a negative charge which makes droplets repel. A liquid film has to be thinned and ruptured before the droplets can interact (Figure 12). Mohammad et al. (2011) observed that an increased salt concentration caused oil droplet size to decrease. They also observed that an increase in oil viscosity resulted in weaker emulsions. An increase of coalescence and size of oil droplets has been observed when oil concentrations were increased dramatically (Lobo and Svereika 2003) (Mohammad et al. 2011).

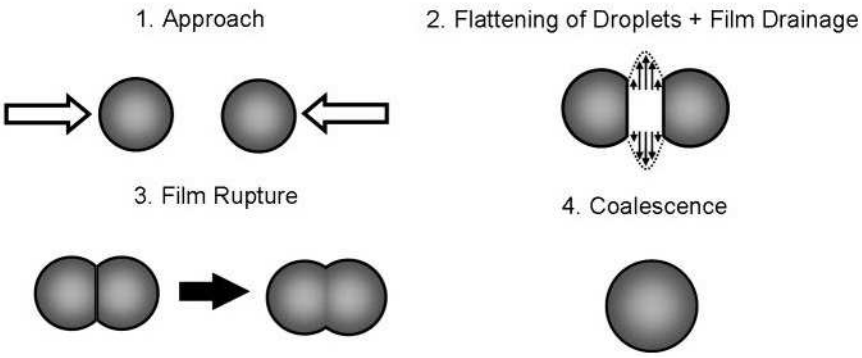

Figure 12. Stages of droplet coalescence (http://wdict.net/word/coalescence+(chemistry)/).

Settling and coalescence are the two most important mechanisms in oil/water separation (Jaworski & Meng 2009), (Hannisdal persmed). Settling velocity is effected by density differences, viscosity, gravity and the droplet size of the dispersed phase. Coalescence is affected by concentration of the dispersed phase and surface properties, and effect the droplet size of the suspended phase. It is common knowledge that when OiW concentration is increased, the amount of coalescence increases because of higher probability of droplet-droplet interactions.

4.5 Topside process equipment

In this chapter process equipment is presented in the order which the fluids is processed at the Oseberg C platform. Starting with valves, which is the pressure and flow reduction step. Than the first separation device, gravity separators are presented. Followed by the hydrocyclones, which is the first separation process in the water treatment system. The process equipment chapter ends with presenting flotation which is the last stage at the produced water treatment system. Separation equipment is first presented in general, before design parameters and operational parameters are presented. The main properties are summarized at the end of each type of equipment presented.

4.5.1 Valves

In the oil industry valves are used to control the pressure and flow in flow systems. The most common valves are choke valves and control valves.

4.5.1.1 Choke valves

Reservoir pressure can be several hundred bars. This is unfavorable for the process system with regard to safety and amount of process steps to apply. Choke valves are installed upstream the topside process system to control the pressure and flow of production stream entering the system. The choke valve is one of the critical points regarded emulsion, because of the high pressure drop over a small volume (equation 4.10). Different choke valve geometry can give different amount of stress. Muntinga (1998) concluded that the valve residence time and energy dissipation was the main factors which cause oil droplets to break up in choke valves. Droplet breakup has been found to occur downstream the valves orifice, and a better valve design should be able to reduce the breakup (Zande et al. 1998).

4.5.1.2 Control valve

Control valves are applied for flow and pressure control, usually before and after process components as separators, hydrocyclones and flotation units. Control valves are also important for process optimization with regards to fluid, gas and pressure control (Ottøy 2013), (Husveg 2007).

4.5.1.3 Typhoon valve

Typhoon valve can be used as both choke valve and control valve. In this work the valve is only considered as a choke valve. The background behind the typhoon valve was to develop a low shear valve that can reduce droplet break up (Husveg et al. 2009a), (Husveg 2007). Low shear effect was believed to reduce emulsion, increase separation efficiency, reduced OiW in the produced water and reduce water in oil. Considering equation 4.10 the most likely solution would be to increase the volume where energy dissipation takes place. One of the designs developed was a cyclonic valve. This valve increased the volume where energy dissipation takes place, and forces a cyclone effect upon the fluids, similar to cyclones in hydrocyclones (Figure 13).

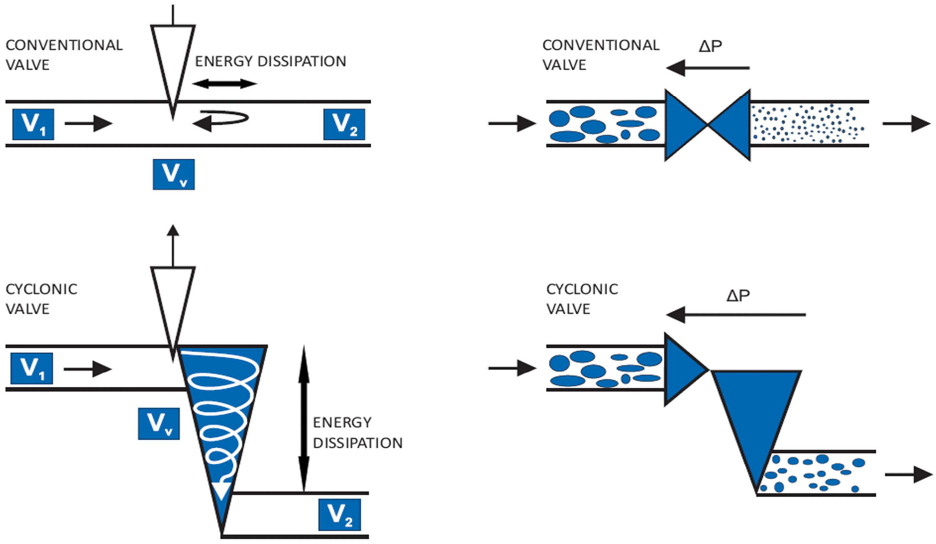

Figure 13. Valve principles and effect on two-phase separation (Typhonix).

During a PhD. program, the valve was tested in laboratory conditions with good results (Husveg 2007). Cyclone valves has been tested further during lab conditions and showed positive results regarding OiW, WiO and generally larger oil droplets in the produced water (Husveg 2009). During these tests it was also observed that the effect of the cyclone valve change from crude to crude. Therefore it would be preferable to conduct pre-study before installing the typhoon valve. Geometry of the typhoon valve is shown in Figure 14.

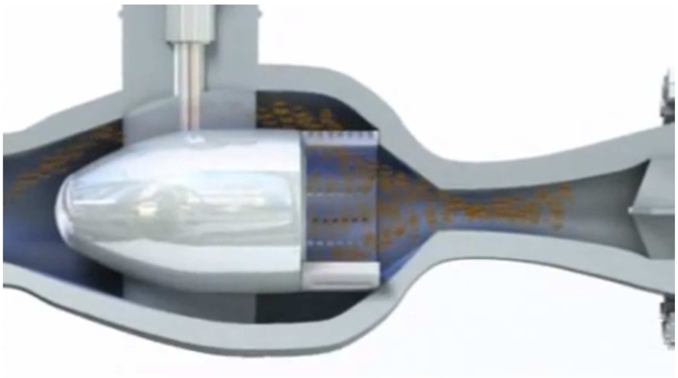

Figure 14. Vertical Typhoon Valve geometry (Typhonix).

4.5.1.4 Valve – summary

It is well known that choke valves increase the emulsions in production fluids. Reducing the amount of emulsions generated in these valves will be a huge benefit for the downstream separation system (Ottøy 2013). It has been observed that the valve configuration has a great importance for the amount of turbulence inflicted (Muntinga 1998), (Zande et al. 1998), (Husveg 2007).

4.5.2 Gravity separators

As the production fluids are transported from the reservoir to a production facility it is mixed rapidly. When the mixture reaches the process plant it has to be separated in to gas, oil and water. The first stage is usually a horizontal three-phase gravity separator, where gas is removed from the liquids, and the water and oil phases are separated roughly (Arnold and Koszela 1990). In petroleum processing oil-water is considered to be hardest to separate, because of the similar density of the liquids (Jaworski & Meng 2009).

Gravity three-phase separators also have a buffering effect when the inlet is surging. Even then, a system upset can result in 10000 ppm of OiW in the water outlet (Orr 2013). Two phase separator can be used to separate gas from fluids, or to separate oil from water if there is a low gas liquid ratio (GLR). In two-phase oil-water separators the gas will follow the oil.

4.5.2.1 Design

Stokes law (equation 4.6) and estimated fluid retention-time or overflow rate and can be used to design and to get a rough estimation of the separation performance of a three-phase separator (Arnold & Koszela 1990). Stokes law is then used to estimate the vertical speed, while the estimated retention-time or overflow rate for a phase gives you the time which the droplet has to settle out. Other important design factors are required capacity, fluid density difference and oil and water droplet size.

Figure 15 describes the basic thoughts behind separator design. Droplet size, droplet distribution and stokes law can be used to determine needed properties of the separator to get the wanted separation (Grødal & Realff 1999), (Hafskjold & Dodge 1989). By calculating the settling speed for the longest path that the smallest droplet which is supposed to be removed will use to separate, can be used to calculate the overflow speed. A problem with this approach is that the average droplet size distribution may not be known in advance, which results in the design being based on assumptions (Hafskjold et al. 1989). Also droplet coalescence is not considered in this approach.

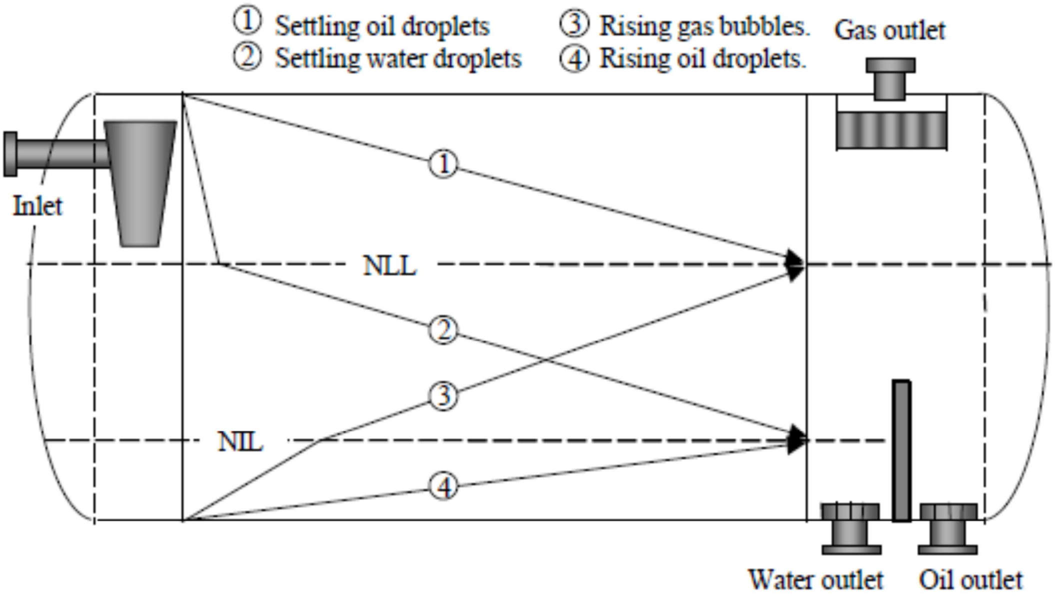

Figure 15. Critical settling paths in three phase separator (Grødal & Realff 1999).

Another approach to design a separator is to obtain the settling design values based on separation data from batch-tests, where clarification zones and phase qualities are measured versus time (Arnold & Koszela 1990), (Magnar persmed). These tests estimates the retention-time needed to get the wanted quality from the phase separation. Bach-tests are more relevant then calculated theoretical settling velocities of the oil droplets, because a theoretical approach does not consider coalescence and particle interference. Software design model has also been developed to maximize separator design (Grødal and Realff 1999). It is common to design the OiW in the water outlet to be maximum 1000 ppm (Æsøy persmed). Separator has to be designed with a wide operating window, because the inlet conditions vary over time.

Separator interior is very simple, to reduce process problems and downtime (Arntzen 2001). Gravity separator interiors have been developed over time to increase the efficiency and reduce the size of the separator (Ottøy 2013). Some well-known components are:

- Momentum breaker reduces the kinetic energy to increase gas/liquid separation.
- Droplet coalescer and demistor, adsorb and coalesce droplets in the gas phase. Coalescer can also be used in the liquid phase to increase droplet coalescence.
- Flow stabaliser makes the liquid flow more uniform.
- Vortex breakers reduce the centrifugal effect of the outlet which otherwise would increase phase mixing.
- Jet water piping, flush out accumulated particles.

Hence, the positive effect, separator internals which increase the surface (i.e. coalescer) are commonly not used because of operational issues (Magnar). Such as scaling and plugging of the equipment which would cause unwanted flow regimes in the separator.

Arnold & Koszela (1990) concluded that the retention-time and overflow-velocity method to design separators gives different results.

The droplet size distribution in the separator inlet flow depends on the amount of stress the oil-water mixture has experienced (Fjeldly et al. 2006). Studies of separation efficiency show that increased droplet size has a major impact on the separation efficiency of oil-water separation (Michaelsen 2003). By separator performance analyses López-Vazquez & Fall (2004) found that OiW decreased rapidly with increased retention-time until a certain level. Beyond this level an increase in retention-time gave little effect. The flow pattern in a separator depends highly on which phase the equipment primarily is supposed to separate (Arnold and Koszela 1990). Because of the high oil viscosity the water droplets use longer time to settle out from oil, than oil use to separate out from water, which is the reason why the main separator primarily is an oil separator in most cases.

4.5.2.2 Operation

Emulsion layer close to the oil/water interphase has a higher viscosity, which reduces the droplet velocity (Choi 1990), (Figure 16). Viscosity of the emulsion layer increase with water cut, until the separator feed becomes water continues, which cause viscosity to drop dramatically, and is further reduced with increased water cut. This support Hafskjold et al. (1994) observations, where they found separator efficiency to increase with increased water cut.

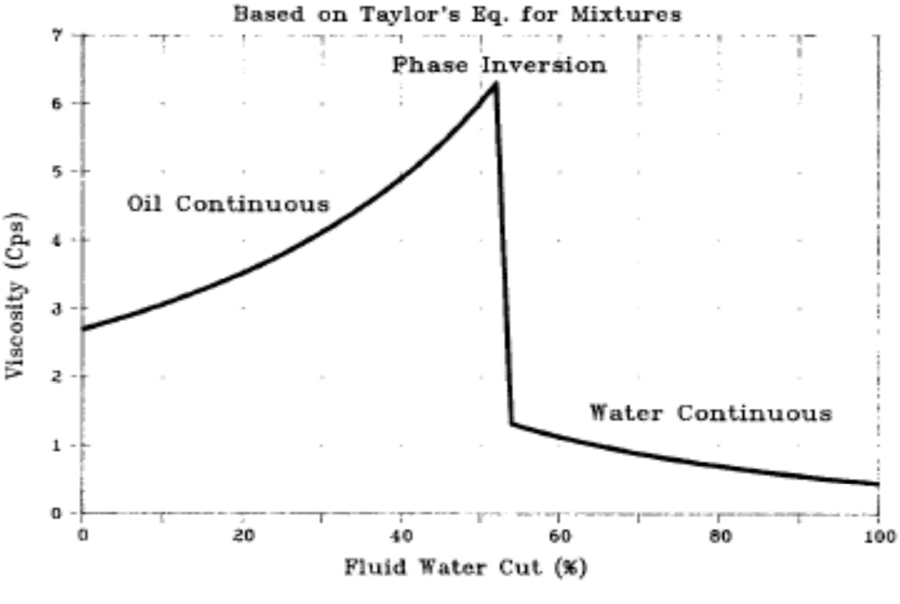

Figure 16. Emulsion viscosity (Choi 1990)

Increasing temperature and pressure has a positive effect on separation efficiency in oil/water separation (Gramme 1999). OiW concentrations out from the separators can be approximately 1000 ppm (Young et al. 1994), (Thew 1986), but will depend on the efficiency of the produced water cleaning system. An example of the relevance retention time has on water quality in gravity settling is shown in Figure 17.

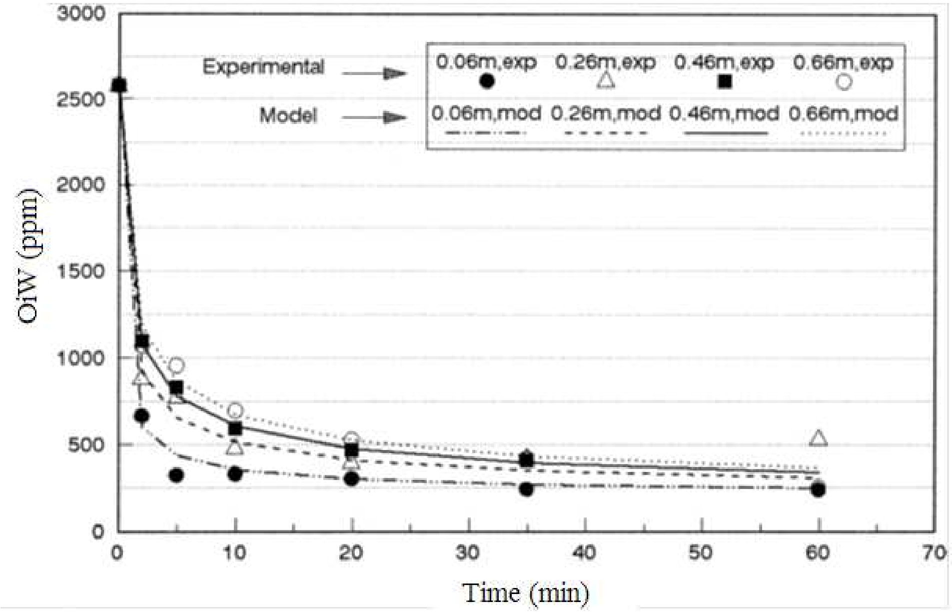

Figure 17. OiW vs. retention time for a batch test study (López-Vazquez and Fall 2004)

Separation function of a three-phase gravity separator is divided into three (Choi 1990): gas-liquid disengagement, oil dehydration and water cleanup. If the available capacity of the separator is to low, production flow or performance of the separation will be reduced, or a substantial amount of chemicals can be used to increase the performance (Hafskjold & Doge 1989).

4.5.2.3 Gravity separator - summary

Gravity separator performance is highly dependent on inlet conditions (droplet size, density differences and emulsion conditions) and flow patterns inside the separator.

Performance of these separators are also influenced by the amount of emulsions and the conditions of continues phase. These emulsions do not only affect the purity of the phase, but also the viscosity when the concentration of dispersed phase is high, i.e. at the oil-water boundary layer.

Droplet size and density difference have a direct influence on the velocity of the oil droplets (equation 4.6). During operation oil droplet size can be increased by using a coalescer or other type of surface increasing devices. But such devises are usually avoided because of operational problems such as scaling and interruption of flow pattern.

The design is usually very simple with nonmoving parts to reduce the amount of necessary maintenance and stop in production. Optimal flow pattern in a horizontal gravity separator is plug flow conditions, because it minimizes the amount of droplets reentering the emulsion.

4.5.3 Hydrocyclones

Hydrocyclones has been used in produced water treatment at almost every offshore petroleum installations since the mid-1980s (Berlandi & Thew 2003). The design of the hydrocyclone use centrifugal forces to increase droplet separation. The simplicity of the unit makes it easy to use and maintain. Hydrocyclones is a well-known tool in separation technology. The first cyclones were developed by Knickerbocker Company in 1885 and were used to remove dust from air, which is gas-solid removal (Newtech.dp.ua). After the invention of the cyclone, it has been further developed for solid-liquid and liquid-liquid separation. Hydrocyclones, also called liners, can be a part of the separation system in different kinds of areas like mining, petroleum, food processing, paper industry, drilling industry and metal working industry. In offshore separation systems, hydrocyclones are mostly configured into pressure vessels with several liners in each vessel (Figure 18).

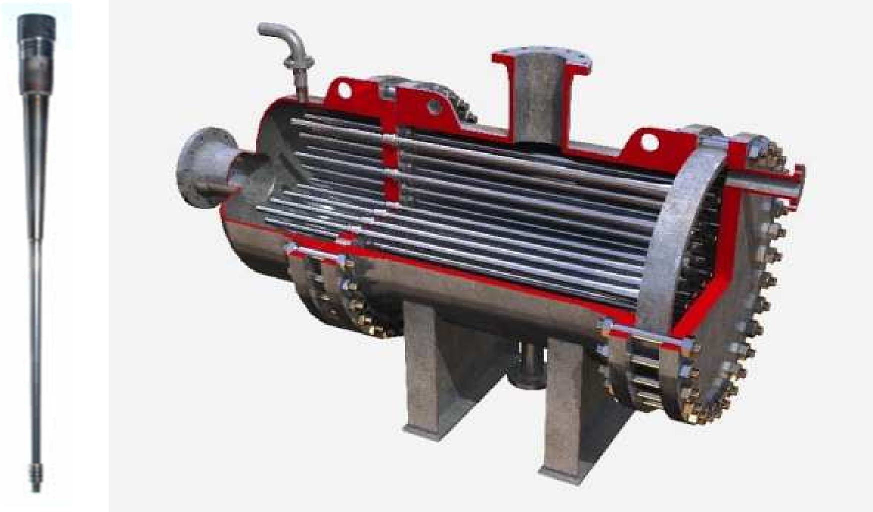

Figure 18. Hydrocyclone liner and hydrocyclone pressure vessel (Finnborud 2013).

4.5.3.1 Hydrocyclone design

Fluid enters the hydrocyclone at high pressure trough one or more vertical inlets to the swirl chamber, which causes a vortex to develop (Figure 19). Multiple inlets are preferred because it gives a more stable flow into the swirl chamber. Separation occurs in the hydrocyclone due to the centripetal forces caused by the vortex which cause the heavy phase to be forced towards the hydrocyclone wall. The lighter phase will migrate to the center of the hydrocyclone and create a reverse vortex flow. This cause the heavy phase to exit trough the underflow, while light phase exit trough the overflow. Reverse vortex can be strengthened by counter pressure from the underflow, created by downstream pressure control or by the underflow geometrical design (Gomez et al. 2001). Vortex finder can be used to stabilize the counter vortex in the hydrocyclone. This equipment is an extension of the overflow pipe going into the swirl chamber. The vortex finder is commonly used in solid-liquid cyclones and liquid-liquid cyclones when the heavy phase is the dispersed phase (Husveg 2007).

De-oiling hydrocyclones usually operate within 2000-3000 g. There is no general hydrocyclone design, because different applications have different demands. Hydrocyclone diameter affects booth efficiency and capacity. When the diameter is reduced the effect increase, but the capacity is reduced (Husveg 2007).

A lot of effort has been focused on optimization of the hydrocyclone design (Berlandi & Thew 2003), (Meldrum 1988), (Svarovsky 1988). Sizing the diameter of the underflow and overflow has been revealed to have a great importance. The overflow orifice size depends on velocity of the flow, and the amount of oily water and the amount of gas exiting the overflow (Gomez et al. 2001). If the overflow orifice is increased, the amount of water following the oil will also increase. Larger orifice makes it possible to separate more oily water and does not affect underflow water purity. It is usually possible to change the overflow orifice to be able to handle changes in conditions. This is an advantage because the amount of gas released or amount of oil in the inlet can change over time. Sizing of hydrocyclone inlets has been researched by Young et al. (1994) and Young (1987) where it has been proposed optimal correlations between cyclone diameter and cyclone inlet diameter. An optimal inlet design increases the hydrocyclones rotational velocity by providing the best spin momentum transfer.

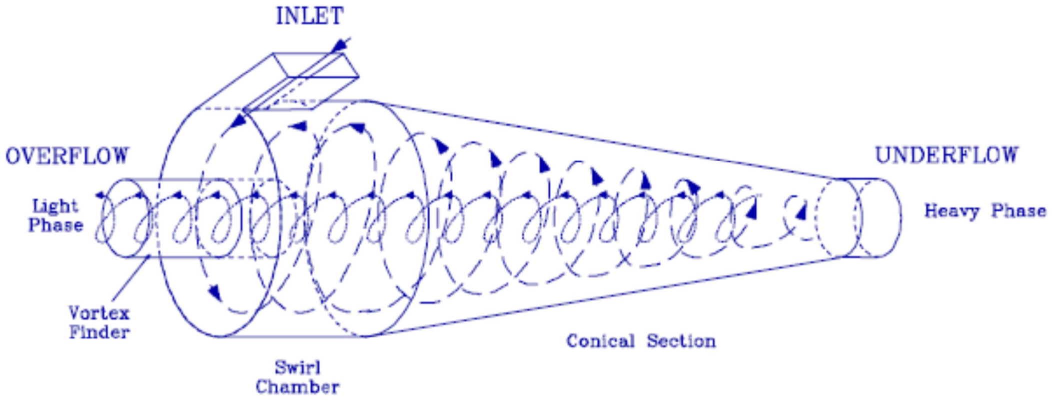

Figure 19. Main cyclone features (Sinker et al. 1999).

4.5.3.2 Hydrocyclone operation

Normal hydrocyclone efficiency can be 80-95 % removal with an overflow rate of 2-3 % of the inlet flow (Berlandi & Thew 2003), (Æsøy persmed), (Orr persmed). Separation efficiency of a de-oiling hydrocyclone can be defined by equation 4.15.

$$E = \frac{C_{underflow}}{C_{inlet}} * 100\% \tag{4.15}$$

E = separation efficiency (%)
$C_{underflow}$ = concentration of OiW at underflow (ppm)
C_{inlet} = concentration of OiW at inlet (ppm)

Separation efficiency is highly dependent of the density difference and the droplet size of the dispersed phase (Sinker et al. 1999), (Medrum 1988), (Young et al. 1994), (Æsøy persmed)

Hydrocyclones have an optimal flow rate area where the separation efficiency is constant for a long range of flow rate (Husveg et al. 2007), (Figure 20). Some flow is needed to get the vortex motion inside the hydrocyclone. When flow is increased further centripetal forces increase, which increases the separation performance until a curtain flow-rate (Q_{min}), (Medrum 1988). The reason why there is a plateau in Figure 20 is that the increase in centripetal forces is equalized by the reduced retention time and droplet brake-up (Thew 2000). At a certain flowrate (Q_{max}) the efficiency will decrease due to shearing of oil droplets and an inefficient pressure at the core of the cyclone which inhibits the reject flow (Medrum 1988).

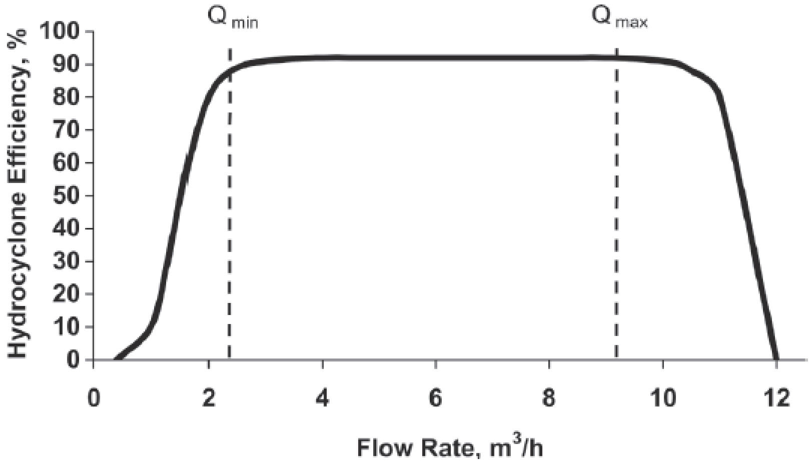

Figure 20. Hydrocyclone efficiency vs. flowrate (Husveg 2007b)

Flowsplit/reject-ratio for a hydrocyclone is the amount of fluid exiting trough the overflow compared to the inlet flow. In oil/water separation with hydrocyclones the reject flow is a flow containing the concentrated oily water. Normally de-oiling hydrocyclones operate with 2-3% reject-ratio (Thew 2000). Separation performance increase when flowsplit is increased, until a certain point where it levels out. An increase in flowsplit beyond this point only gives marginal improvements in efficiency (Figure 21), (Medrum 1988). Medrum (1988) found flowsplit of 1% to be enough to reach the plateau for oil removal efficiency for hydrocyclone operation at two offshore platforms. It is beneficial to have as low flowsplit as possible to reduce the amount of water which gets recycled into the oil-train (Finborud 2013). However, some water has to follow the oil through the overflow to get an exactable efficiency.

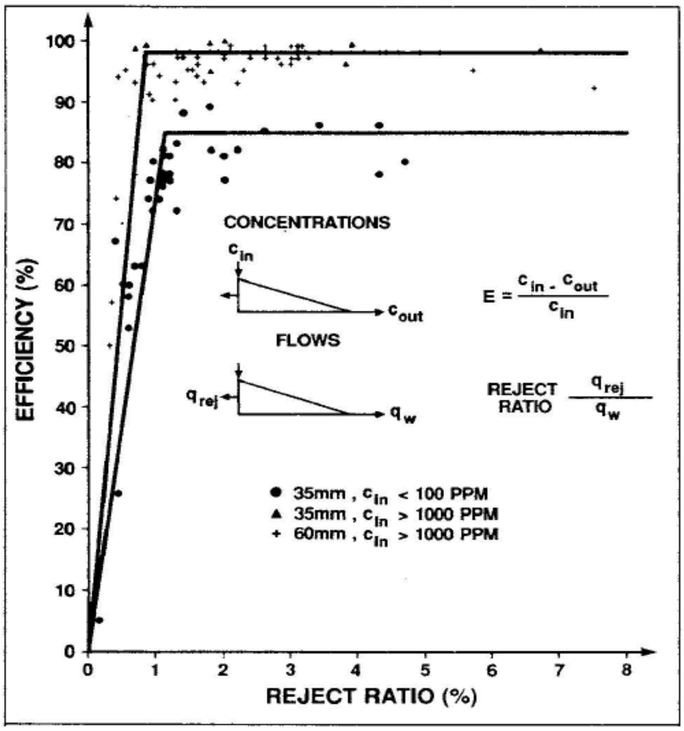

Figure 21. Hydrocyclone efficiency vs. reject ratio (Medrum 1988).

Process control systems can be added to monitor and adjust the flowrate and flowsplit through cyclones to get an optimal separation (Husveg 2007). This is necessary because the produced water has a dynamic flow. Hydrocyclone retention time is typically a few seconds. Because of the low retention time it is very important to operate hydrocyclones under optimized conditions.

4.5.3.3 OiW dependence

Experience from hydrocyclone performance has given conflicting results. Medrum (1988), Colman et al. (1980) and Thew (2000) found that increasing oil concentration lead to increasing hydrocyclone performance. They believed that the concentration increase caused droplet coalescence to occur more frequently and thereby increase the oil-droplet size. It seems like most literature conclude that changes in the OiW inlet has no effect on the relative performance (Young et al. 1994), (Gomez et al. 2001), or that change in the OiW inlet would have none or little effect on the hydrocyclone efficiency (Thew 1984), (Colman et al. 1980), (Seureau et al. 1994). Statoil has not observed any obvious trends during operation regarding hydrocyclone and OiW dependence (Æsøy persmed).

4.5.3.4 Hydrocyclone - summary

Hydrocyclone operation performance depends on design, inlet conditions and operational control. Design variables are diameter of cyclone, diameter of cyclone inlet, underflow outlet and overflow outlet. Changes in the inlet conditions can be droplet size, density differences and OiW concentration. Operational control includes flow control, pressure control and control of the flow split.

A small cyclone diameter yields a hydrocyclone with low flow and high separation performance. If the diameter is increased the cyclone separation performance decrease, but it can handle a higher flow-rate. For each cyclone diameter there is an optimal cyclone inlet diameter providing the best spin momentum transfer. The underflow outlet must be designed to give sufficient back pressure to get sufficient separation, unless there is components downstream supplying backpressure. Overflow outlet has great importance.

Hydrocyclone performance is highly dependent of dispersed droplet size and the density differences between the phases. This can be explained directly from stokes law modified to explain centripetal acceleration (equation 4.9). If droplet size and/or the differential density are increased, separation performance also increases. Research carried out on hydrocyclones and its dependence on OiW concentration has not come to an agreement.

4.5.4 Flotation unit

Flotation technology is widely used in water treatment. The technology use small gas bobbles to increase separation of small particles, oil droplets and in some cases also dissolved oil (Hayatdavoudi 2011), (Bennet 1998), (Bensadok et al. 2007). Both gas and oil (usually) are less dense than water. This cause both oil and gas to rise when they are suspended in water. Gas bobbles are less dense and usually larger than oil droplets. This cause gas bubbles to rise faster than oil droplets, which cause them to collide (Strickland 1980). Gas bobbles can attach to or be encapsulated onto oil droplets or flocks, which reduce the density of the oil droplets. According to Stokes law (equation 4.6) this increase particle speed and thereby separation efficiency. Oil-gas coalescence causes flotation units to have a low dependency of oil density. This is because of the high density difference between the oil-gas and water (Kornberg persmed).

There are two types of gas flotation:

DGF (Dissolved gas flotation) is an approach where the liquid pressure is reduced when the gas saturated liquid enters the flotation unit. Due to the new conditions the liquid is oversaturated with gas and as a result small air bobbles is created. The sizes of the bobbles are typically 10-100 µm (Moosai and Dawe 2002). In a degasser high amount of gas is usually released due to the pressure-drop. If the inlet to the degasser is beneath the gas/liquid surface, flotation can be optimized (OPUS-Results.com).

IGF (Induced gas flotation) is the approach where gas is injected into the flow stream, and small bobbles (100-1000 µm) can be made by using a sparger and impeller or inductor (Moosai and Dawe 2002).

Gas bubbles generated in DGF are smaller than bubbles made by IGF (Couto 2005). Smaller bobbles are preferred in water treatment because it increases collision efficiency by increasing the area of gas surface per volume (Lee et al. 2007), (Moosai and Dawe 2002). But when bobbles decrease in size, so does the flotation velocity of the bobble. Large bubbles can be negative due to higher velocity which reduces the contact time during bubble-droplet interactions and create turbulence in the water. Turbulence created can cause oil droplets to reenter the water after oil/gas contact.

4.5.4.1 Oil and gas coalescence

When an oil droplet and a gas bubble collide, there is a thin water layer between them that has to rupture for them to interact (Strickland 1980), (Oliveira et al. 1999). The contact time has to be longer then the rupture time for an interfacial deformation to occur, and depends on the surfactant affinity of the phases involved. Strickland (1980) defined successful flotation to be when *the "oil droplet attach to the gas bobble after collision and must remain attached until the bubble reaches the surface of the flotation cell"*.

Probability for flotation (P_f) is found to be dependent on probability of collision (P_c), probability of adhesion (P_a) and the probability for stable aggregate formation (P_s) (equation 4.16), (Oliveira et al. 1999).

$$P_f = P_c * P_a * P_S \tag{4.16}$$

Collision efficiency (E_c) is the number of particles that effectively collide with a bubble (Strickland 1980), and can be described by equation 4.17.

$$E_c = \alpha_0 (\frac{d_p}{d_b})^N \tag{4.17}$$

α_0 = proportionality factor
d_p = diamerter of the particle
d_b = diameter of bubble
N = an exponent depending on the density of the particle/droplet and fluid

Performance of the flotation unit is highly dependent on the probability of contact between gas bubble and oil droplet, and the velocity of the oil/gas particle (Lee et al. 2007). Efficiency can be reduced in flotation systems if there are large deposits of oil at the oil/water surface. This is due to increased possibility of oil reentering the flow.

There are three types of physical mechanisms that can occur between oil droplets and gas bubbles (Frankiewicz et al. 2005). An impact between oil droplet and gas bobble can cause the oil droplet to: coat the gas bubble, stick to the gas bobble or be pulled by the gas bubbles when they rise to the surface. Lee at al. (2007) stated that *"Regardless of the type of attachment that occurs, the strength of the bonding is determined by the surface of the contact region between the gas bobble and oil droplet."*

The spreading factor, S_0 (equation 4.18) indicates if spreading of the oil droplets is possible. Sylvester and Byeseda (1980) assumed oil droplet adsorption to gas bobbles and gas bobble absorption into oil flocks to be the main oil/gas interactions. Several others believed oil droplet adsorptions to gas bobbles to be the main flotation force with small bobbles and drops (Lee and Frankiewicz 2004), (Moosai and Dawe 2002).

$$S_0 = \gamma_{wg} - \gamma_{ow} - \gamma_{og} \tag{4.18}$$

Υ_{wg} (water/gas surface tension) has to be higher than the sum of surface tension between oil/water (Υ_{ow}) and oil/gas (Υ_{og}) for spreading to occur (Grattoni et al. 2003). The principle of oil/gas flotation, by spreading and no spreading, is shown in Figure 22.

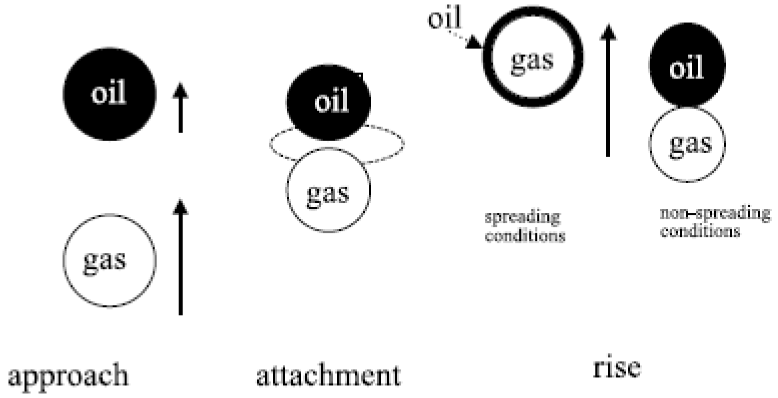

Figure 22. Oil droplet coating gas bubble (Grattoni et al. 2003).

4.5.4.2 Flotation unit design

When a flotation unit is designed it is important to avoid zones without gas bobbles and recirculating zones to get optimal efficiency (Ottøy 2013), (Bennet 1988) and (Johansen persmed). Other factors that are important for collision efficiency is gas flow-rate, bobble size distribution and chemicals added. Welz et al. (2007) observed that the rate of agitation and aeration improved the oil rate removal. Frankiewicz et al. (2005), Lee et al. (2007) and Sylvester & Byeseda (1980) has found that the droplet-bobble collision efficiency inside a flotation unit can be maximized by obtaining uniform flow of produced water and gas, optimizing the size of the gas bobbles and increasing oil droplet/particle size. Leech et al. (1980) found rotor diameter, skim rate and oil concentration to have little effect on the removal rate. Flotation units are usually horizontal and have a generally high requirement of footprint and residence time (Figure 23). Offshore installations are compact, and the footprint well used. Development of vertical flotation units has resulted in more compact and effective units (Daigle 2012), (Hayatdavoudi 2011), which are more suitable for offshore installations.

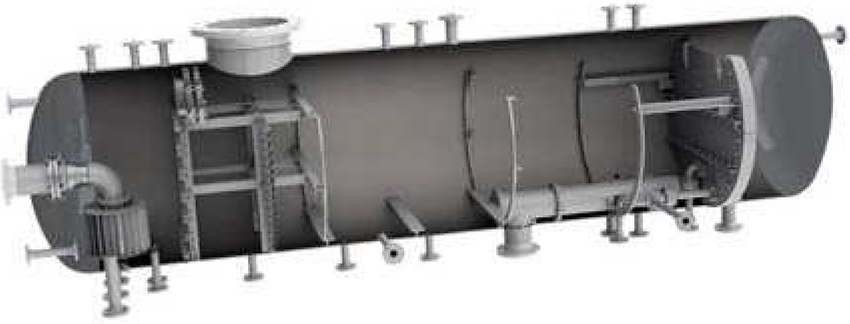

Figure 23. Horizontal degasser design, OPUS (OPUS-Results.com)

4.5.4.3 Flotation unit operation

Sylvester & Byeseda (1980) did not find gas flow rate to have any effect at the removal rate in range of practical operation. When fluid flow rate is increased the oil removal rate may decreases because of an increase of bulk velocity toward the water outlet. Droplets which would barely be able to float to the surface at lower flow rate will exit trough the water outlet. Leech et al. (1980) observed that increasing the inlet flow rate to 140% of design value did not have an impact on the optimal oil-removal efficiency. Moosai and Dawe (2002) determined efficient skimming of floated oil and an efficient chemical program to be important for the efficiency of a flotation unit. From experiments Stricland (1980) revealed that flotation efficiency increased when gas bobbles size decrease and when the amount of collisions, salinity, temperature, attachment efficiency and gas/liquid contact time increased. Salinity has been observed to reduce the gas bobble size (Kornberg persmed), (Stricland 1980). Sylvester & Byeseda (1980) got similar results, but also discussed that the salinity could have a destabilizing effect on the oil droplets. Minimum retention time for degassers has been found to be 60 seconds for degassing and 90 seconds for efficient oil removal (Æsøy persmed).

4.5.4.4 Flotation unit kinetics and OiW dependence

In general oil in water removal with gas flotation tends to follow first-order kinetics (equation 4.19), (Angelidou et al. 1977) (Niemi 1995), (Sylvester & Byeseda 1980).

$$\frac{dC_p}{dt} = -KC_p \tag{4.19}$$

C_p = Concentration of oil particles
T = Time
K = Rate constant

Couto et al. (2005) experienced good correlation between estimated and test data, when they assumed the flotation kinetics to be first-order. Some studies indicates that OiW removal with flotation follow second-order kinetics (Welz et al. 2007)

The equation (4.19) can somehow be misleading because the rate constant can change when conditions are changed (Angelidou 1977), (Qi et al. 2013). However, particle concentration was not found to have any significant effect. The gas flow rate has been found to have a high influence on the rate constant (Angelidou 1977), (Pal & Masliyah 1990).

Bensadok et al. (2007) used a DAF unit to treat wastewater with cutting oil (soluble oils). Two different oils were used. For one of the oils, adjusting OiW concentration gave no effect on separation efficiency, while the second oil had an increased efficiency when the inlet OiW concentration was increased. Cline (2000) presumed IGF to be relatively independent to inlet oil concentration.

Moosai and Dawe (2002) concluded that concentration of oil, density of oil, oil droplet and gas bubble size, chemicals, salinity and viscosity of aqueous phase were important variables which influence flotation performance. Results from a flotation column and a jet flotation study showed that an increase in inlet oil concentration reduced the flotation efficiency (Pal and Masliyah 1990), (Santander et al. 2011). Strickland (1980) revealed that separation efficiency increase when OiW were increased, and believed that an increase of OiW had a positive effect on oil droplet coalescence. Or that gas bubbles already coated with oil have a higher probability to be coated by oil droplets. Qi et al. (2013) found the efficiency constant to depend on OiW concentration. Æsøy (2013), Mclellan (2013) and Johansen (2013) have not observed any obvious correlations between OiW inlet concentrations and separation performance.

4.5.4.5 Flotation unit - summary

Degasser operational performance depends on physical and chemical conditions in the degasser. Physical conditions with great importance are design, flow rate, amount of particles, OiW concentration, droplet and bubble sizes. Chemicals of importance are the ones affecting the surface conditions, like corrosion inhibitors, scale inhibitors and hydrate inhibitors.

It is important with a good design to minimize the dead spots in the unit and to increase water and gas distribution. These are conditions affecting collision efficiency, which have a direct impact on separation performance.

When flow rate is increased the overall downward velocity in the separation unit increases. An increase in downward velocity can cause a reduction in performance because some oil/gas bubble/particles may not have sufficient flotation velocity.

Particles in the produced water can adsorb to the oil droplet interphase, causing the droplet to stabilize, thereby reducing the possibility for oil droplets and gas bobbles to coalesce. The effect is similar to the one caused by surface active production chemicals. Surface active chemicals increase the zeta potential and cause droplet to be more stable.

An increase in oil droplet size will increase the possibility of flotation. Possibility of flotation also increase when gas bubble size decrease. Small bubble size gives lower rising velocity than bigger bobbles.

In relation to OiW concentration, separation has been found to follow first-order kinetics. However, the efficiency does seem to have a small reduction when concentration is reduced.

4.6 Disposal of produced water

Produced water can be disposed of into the sea or be injected into a reservoir. If it is disposed to the sea, there is a demand for dispersed oil being less than 30 ppm in average, at the Norwegian continental shelf (OSPAR). For injected water there is no demand for the concentration of oil dispersions. But it is well known that oil and particles in the produced water can reduce the permeability of the reservoir (Mohammad et al. 2011). Therefore it is known praxis to treat the water to reduce the amount of well work-over needed. Another reason for treating produced water even if the water is going to be re-injected is that there can be operational problems with the reinjection system (Ottøy 2013). Than the water has to be discharged to sea or the production has to be stopped. To stop the production is costly, both in money not earned because there is no production and the high cost of the personnel on the rig.

4.7 Relevance of cleaner water in the future

For now it is enough to have less than 30 ppm of dispersed oil in the discharged produced water (OSPAR recommendation 2001/1). Operators may have internal objectives to reduce the concentration of OiW even further than the discharge demands (Johansen 2013).

The time to initiate operation in colder and more sensitive areas is approaching. When it comes to waste discharge in these areas a zero tolerance is expected (Æsøy 2013). This implies that close to all produced water has to be re-injected or totally polished before it is discharged.

Even if the produced water is going to be re-injected there are demands for the purity of the water. The reasons are first of all that the water has to be clean to avoid a reduction of the permeability in the reservoir (Mohammad et al. 2011). Another reason to clean the water before it is re-injected is that the injection system can malfunction or may have to be maintained (Ottøy 2013). Then it is important to clean the produced water to be able at discharge it to sea to avoid unnecessary stop in production.

For the last polishing/cleaning stage it is important to have as low OiW concentration as possible (Æsøy 2013). For example if membranes are supposed to be used in the last stage, a reduction in the upstream OiW concentration can reduce the amount of maintenance that the membranes would need. The reduction of OiW can also increase the lifetime of the membranes. The effect of other polishing steps would also benefit from less OiW. Other examples for polishing steps can be oxidation and adsorption.

5 RESULTS AND DISCUSSION

As an introduction to this chapter a couple of assumptions about the process system at Oseberg C will first be addressed and discussed. These assumptions will be fundamental for the calculations to be carried out. Average values for OiW in the produced water system using standard valves have been calculated, using basic percent calculations. Concentration of OiW out from the separator, if typhoon valves had been installed, have been calculated by using effects obtained from the pilot test at Oseberg C. OiW at the water discharge were revealed by using basic percent calculation and separation performance for hydrocyclones and degasser. The amount reduction in use of flocculants which can be expected has also been calculated. Results and calculation has been discussed along the way. At the end of this chapter the overall results are summarized.

5.1 Assumptions

Some assumptions had to be made for the process system to be able to calculate how the performance of the produced water treatment would be, if all choke valves where replaced by typhoon valves at Oseberg C.

5.1.1 Fluid characteristics

All other parameters than OiW are assumed to be the same in the separators water outlet independent of valve type. The reason for this assumption is that the separator treats the "same" water. Because the results describes how OiW would have been if typhoon valves had been installed instead of standard valves. In this theoretical approach standard valves and typhoon valves are assumed to process the exact same fluids. Under real conditions this could not have been done at a platform, because it is not possible to choke one well with two different chokes at the same time.

This assumption is a basic fundament which makes it possible to compare the effect typhoon valve can have on the produced water system. As all people in the petroleum industry know, the production rates and composition change over time. The assumption above makes both types of valves operate at exactly same conditions. Which otherwise would only be able to occur at laboratory conditions.

The average droplet size (D_{50}) was found to be the same during the pilot test (Eidsmo et al. 2012). Therefore the D_{50} has been assumed to be the same at the produced water outlet of the separator when using both types of valves.

5.1.2 Effect on wells

Test data on typhoon valve performance only exist from one well (Eidsmo et al. 2012). To be able to calculate overall performance the effect from changing the choke valve to a typhoon valve is assumed to give the same effect on all the wells.

When the water-cut is close to 50% oil-water separation is known to be problematic due to an increase in viscosity of the emulsion layer close to the oil-water interphase (Choi 1990). During the pilot test the OiW concentration were in this level. From earlier testing, the typhoon valve has not been observed to give this high advantage under these process conditions (Husveg et al. 2009 a & b). The lowest benefits for the typhoon valve have been observed at 50% water cut. Therefore, if the water-cut of the well-streams were to differ from the pilot test, performance of the typhoon valve is not believed to have a reduced relative effect compared to a standard valve. However, the effect is believed to be positive. But to what degree this effect would be is hard to predict.

5.1.3 Oil in water

As mentioned earlier a lot of experience in separation technology is gained by hand on experience and learning by doing. It seems like there is a general understanding that when OiW is reduced the efficiency of the produced water treatment system is reduced (Mclellan 2013), (Medrum 1988), (Colman et al. 1980), (Thew 2000). But it is not always like that (Chapter 4.5.3.3 and 4.5.4.4).

The assumed reason why there is a strong belief that less OiW is harder to treat, may be that a reduction of OiW often is associated with an additional separation device upstream. Then the reduction of OiW would result in an emulsion which is harder to treat. This is because the larger oil droplet would be removed by the additional device. This device could for example be a coalescer in the main separator which would increase the oil-water separation. This kind of equipment reduces the OiW out of the separator, but the D_{50} of the oil droplets in the produced water will also be reduced. This would have a negative impact on the relative performance of the produced water treatment system compared to before the coalescer had been installed. This is because more of the larger droplets would settle out in the gravity-separator.

When a typhoon valve is installed it replaces an already existing valve. The typhoon valves design reduces the droplet breakup. As mentioned earlier the droplets D_{50} were the same during the pilot test and have been assumed to be the same in this thesis (Eidsmo et al. 2012). By replacing a standard valve with a typhoon valve, OiW is reduced while the D_{50} is the same. This reduction of OiW has then been assumed to propagate throughout the produced water system (Finborud persmed and Mclellan persmed).

5.2 Calculations and discussion

The calculations are based on average values for both separation efficiency and OiW concentrations. An important first step was therefore to calculate the yearly average OiW in the produced water discharge. Average OiW (OiW_a) in the produced water were calculated by using yearly water production (V_{pw}) and yearly mass of dispersed oil (M_o) released with the produced water. The values were obtained from the yearly discharge report for the Oseberg field (Bratteteig & Dalsrud 2013).

$$OiW_a = \frac{M_o}{V_{pw}} = \frac{7700000g}{536688m^3} = 14{,}3\frac{g}{m^3} = 14{,}3ppm$$

Degasser efficiency has been given from Statoil to be 15% (Knudsen percom). By using the degasser efficiency and the OiW concentration at the outlet (OiW_o), OiW concentration at the degasser inlet (OiW_i) were calculated.

$$OiW_i = \frac{OiW_o}{1 - E_d} = \frac{14{,}3ppm}{1 - 0{,}15} = 16.8ppm$$

Further the efficiency of the hydrocyclones was given by Statoil to be 75% (Knudsen 2013). This efficiency is similar to separation performance results from tests conducted by Mator (Heitman 2011), (Berntsen 2011). By using the hydrocyclone efficiency (E_h) and inlet OiW concentration to degasser, OiW concentration (OiW_s) in to the hydrocyclone were calculated. The inlet concentration of OiW to the hydrocyclones is the same as the concentration at the water outlet of the separator (OiW_S).

$$OiW_s = \frac{OiW_o}{1 - E_h} = \frac{16{,}8ppm}{1 - 0{,}75} = 67.3ppm$$

Knudsen (2013) agreed that OiW out of the separator approximately 70 ppm would be reasonable for the separation system at Oseberg C.

From the pilot test at Oseberg C one of the benefits was found to be a 55% average reduction of OiW concentration at the separator water outlet (Eidsmo et al. 2012).

By assuming this benefit to be relevant for all the wells at Oseberg C, and that all choke valves were replaced with typhoon valves (Chapter 5.1.2), OiW at the separators water outlet (OiW_T) was calculated.

$$OIW_T = OIW_S \cdot (1 - 0{,}55) = 67.3ppm \cdot (1 - 0{,}55) = 30.3ppm$$

Hydrocyclones efficiency is mainly dependent on the fluid flow, split ratio, pressure drop rate and the oil droplet diameter (Sinker et al. 1999), (Medrum 1988), (Husveg 2007 a & b), (Thew 2000). Here the droplet size has the largest influence. In this research changes in OiW concentration is assumed to be the only parameter changing when standard valves are replaced with typhoon valves (Chapter 5.1.1). There are some disputes about how changes in OiW will affect a hydrocyclones performance (Chapter 4.5.3.4). Even then, most of the articles and other information gathered proposes that hydrocyclones is not, or very little affected by changes in OiW concentration (Young et al. 1994), (Gomez et al. 2001), (Thew 1984), (Colman et al. 1980), (Seureau et al. 1994), (Æsøy 2013), (Mclellan 2013). Changes in OiW have not been assumed to give any influence on hydrocyclone performance. OiW values out of the hydrocyclone were found by using 75% separation efficiency (E_h).

$$OiW_o = OiW_i \cdot (1 - E_h) = 30.3ppm \cdot (1 - 0{,}75) = 7.6ppm$$

Then the effect of the degasser had to be found. A degasser is highly dependent on flotation to get an efficient separation of small oil emulsions. Flotation in general is dependent on a lot of parameters which has been mentioned earlier (Chapter 4.5.4.4). By referring to Chapter 5.1.1 the only parameter which is assumed to change is OiW concentration. In general, flotation unit's removal efficiency has been revealed to be unaffected by OiW concentration, and to follow first-order kinetics (Angelidou et al. 1977) (Niemi 1995), (Sylvester & Byeseda 1980), (Equation 4.19). The constant in the first-order equation (4.19) can somehow be misleading because it is affected by physical and chemical conditions (Qi et al. 2013), (Angelidou 1977), (Pal & Masliyah 1990). In a rather new study, the effect different parameters had on the k-value in a first order equation for a flotation unit was investigated (Qi et al. 2013).

K value and OiW concentration from Qi et al. (2013) were plotted. An exponential expression which explained the change in k value as OiW concentration were changed, were revealed and had a good correlation (R^2 = 0.9729), (Figure 24). Even better correlation was revealed using polynomial expression. But with little reference date this kind of trend-line will always get good correlation. Data needed for the further estimations are outside the plotted area, an exponential equation is therefore preferred.

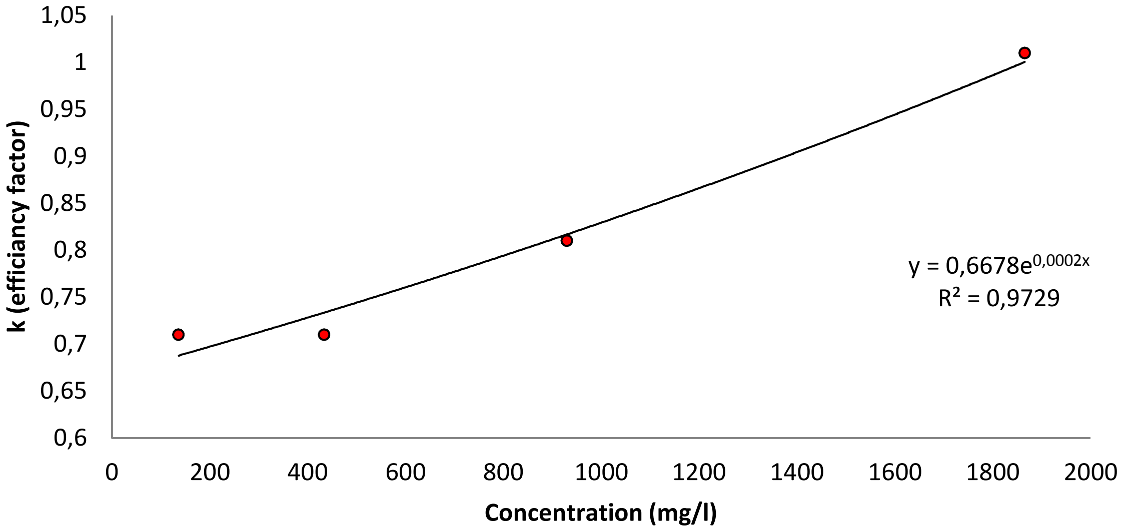

Figure 24. Correlation between efficiency and inlet OiW concentration for flotation units.

Figure 25 were made using the equation from Figure 24 and possible OiW inlet concentrations. The left axis show a wide range of possible OiW concentrations that can occur at the degasser water inlet using a standard valve. The right axis show assumed OiW concentrations at the water inlet using a typhoon valve at the same production flow conditions, but with 55% less OiW.

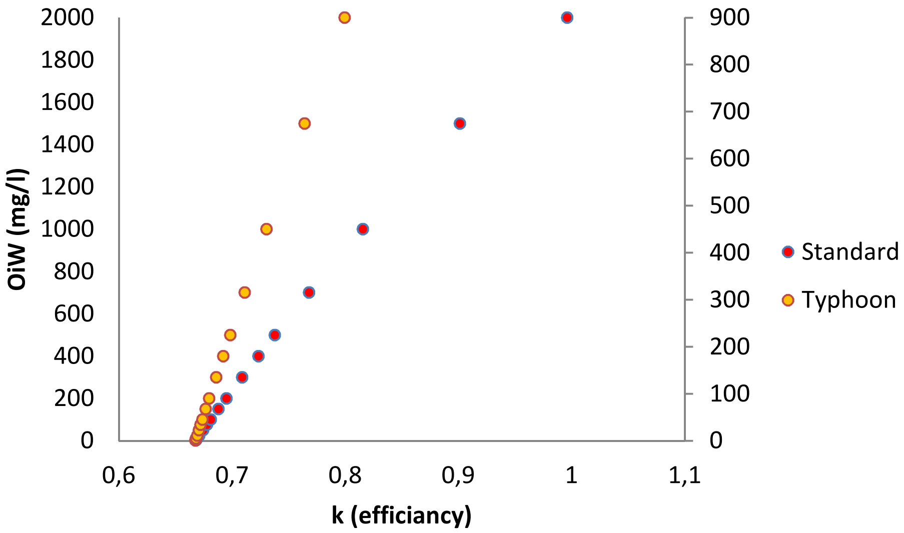

Figure 25. Variation in efficiency (k) of a flotation unit using typhoon valve compared to a standard valve, when OiW reduction caused by typhoon valve is 55%.

By comparing the efficiency constants from Figure 25 the relative efficiency drop when using typhoon valve compared to a standard valve were estimated. The results are given in Figure 26 where the efficiency drop is presented as a function of inlet OiW using standard valve. For example, if OiW into the degasser is 200 ppm when using standard valve and 90% efficiency is expected, the water outlet concentration would be 20ppm. If the typhoon valve were used, the inlet OiW concentration would be reduced by 55% which would cause the OiW to be 90 ppm. An efficiency of 90% is expected, but referring to Figure 26 there will be a 2.2% reduced relative efficiency. This would cause the efficiency to be 88%. The OiW at the water outlet will then be expected to be 10.8 ppm.

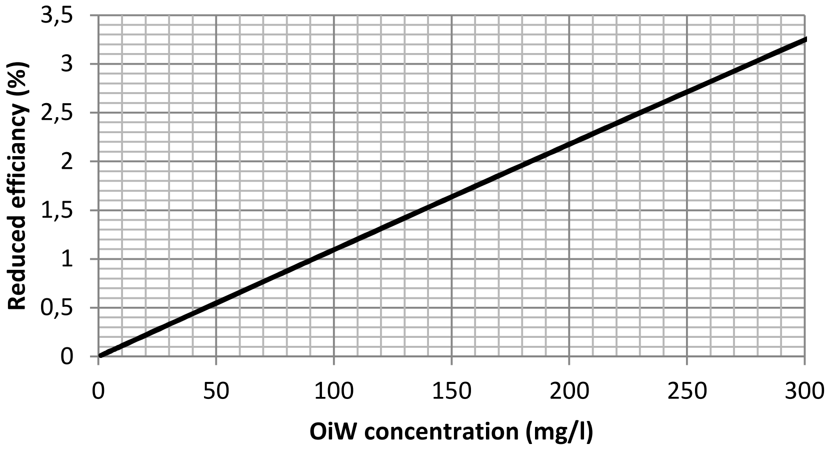

Figure 26. Overview of the efficiency drop that has to be accounted for when using typhoon valve as choke valve, compared to the OiW values that would exist at the degasser inlet if using a standard choke.

The study that the data plot was taken from was actually based on produced water containing flooding chemicals (Qi et al. 2013). But plot data for OiW concentration and k value has not been observed in other research. From the data plot that has been used, OiW were the only parameter that was changed. Also, the values have only been used to find relative reduction. The k-values themselves has not been used. Therefore this approach to find changes in relative efficiency has been assumed to be a better approach, instead of just assuming that the unit is unaffected by changes in OiW.

These findings were used to estimate the effect that the reduction of OiW would have on the degasser at Oseberg C. A reduction in relative efficiency was found to be 0.1% because of the low OiW operating conditions (Figure 26). Thereby the flotation efficiency is maintained at 15% (E_d).

$$OiW_o = OiW_i \cdot (1 - E_d) = 7.6ppm \cdot (1 - 0{,}85) = 6.4ppm$$

Low OiW concentrations cause the effect of the relative efficiency to be negligible. However, for other installations there may be a reduction in efficiency because the operational conditions may be different.

When the OiW concentration at the water discharge when using the typhoon valve was known, the total difference in oil discharged with the produced water (M_{OR}) was calculated. Yearly oil discharged to sea during 2011 was multiplied with the difference in concentration in the discharged produced water.

$$M_{OR} = M_O \cdot \left(1 - \frac{OiW_T}{OiW_S}\right) = 7{,}7ton \cdot \left(1 - \frac{6.4ppm}{14{,}3ppm}\right) = 4.25ton$$

5.3 Flocculent reduction

In 2011, 20 ton of a flocculent (F) with part number WT-1387 with yellow category were used at Oseberg C (Bratteteig & Dalsrud 2013), and the flocculent is injected upstream the hydrocyclones. The reduction of flocculent (F_r) needed were calculated by using equation 4.5 and information presented in Chapter 4.3.5.1 (Finborud 2013), (Waage 2013).

$$F_r = F \cdot \frac{OiW_T}{OiW_S} = 20ton(1 - \frac{30.3ppm}{67{,}3ppm}) = 11ton$$

Values for production chemicals in discharge reports are given in mass of the chemical (concentrated/dry form). Flocculants are usually 10-30% of the mixture, while the rest is ethylene glycol (MEG) and solvents, which is water in this case (Finborud percom). Then total amount of flocculent reduction is actually 36.7-110 ton per year.

The amount of flocculants at Oseberg C can obviously be reduced by a significant amount by reducing the OiW concentration. But the effect could be somehow lower than the amount of flocculent reduction reveled. Because when the concentration of oil is reduced, there is less chance for the flocculent and oil droplet to collide (Finborud persmed and Waage persmed). It has not been found any method to predict this effect. Thereby it is only possible to speculate that the reduction in use of flocculent would be somehow lower than the reduction revived in this calculation.

Under operation OiW concentration, oil droplet size and the water flux is constantly changing, which makes chemical dosing challenging (Finborud persmed and Waage persmed). However, these problems will be the same when using standard and typhoon valve. So there is no reason to believe that the positive effect will not occur.

Flocculent density has been assumed to be 1.2 ton/m^3. This assumption is based on that MEG has a density equal to 1.11 ton/m^3 and that 10 – 30 % of the mass is flocculent. The amount of MEG is not known. The rest of the mixture is water which is assumed to have approximately 1 ton/m^3. Density is based on assumed values and is used to represent potential benefits. The reason why the amount of flocculent is converted to volume is that flocculent price is only roughly known in liter. Volumes of reduced amount of flocculants were then calculated.

$$V = \frac{Mass}{Density} = \frac{36.7ton}{1.2\frac{ton}{m^3}} = 30.6m^3 \qquad V = \frac{Mass}{Density} = \frac{110ton}{1.2\frac{ton}{m^3}} = 91.7m^3$$

Flocculants are relatively cheap, usually costing about 10 NOK per liter (Kroknes 2011). The yearly cost reduction due to less use of flocculants will then be 0.3 – 0.92 million NOK per year. There are also other costs related to the use of flocculants, such as transport and system upgrades costs. The cost reduction related to transportation will be proportional to the reduction of flocculent used. Because then the amount of times the platform has to be supplied with flocculent would be reduced equally to the reduction of flocculent.

The amount of produced water increase over time as the reservoir matures (Ottøy 2013). Reduction in use of flocculants can extend the lifetime of a chemical system. A chemical system would at least have a cost of 10 million NOK and up to 2 – 3 times more than that if a new chemical tank is needed (Kroknes 2011). Yearly it is normal to use about 200 000 NOK in maintenance on a chemical system to extend the lifetime of the system. Maintenance would of course also be needed if the system is upgraded. Delaying a system upgrade is economically beneficial.

5.4 Separator and produced water system capacity

5.4.1 Separator capacity

Main gravity separators capacity is highly dependent of the required water quality out of the separator (Young et al. 1994), (Thew 1986). The influence retention time has on water quality in gravity separation is shown in Figure 17. A suggestion of how the effect on the water outlet of a separator could be, by replacing standard valves with a typhoon valves is sown in Figure 27. Composition, emulsion type and droplet size upstream the chokes are important factors that influence the improvement of a low shear choke valve (Hannisdal 2013). If the retention time could be reduced by 10% it would be possible to increase production with 11%. An increase in separator efficiency would also depend on the capacity of the gas and the produced water treatment facility. In this case it is known that the produced water treatment facility can treat at least three times more than it did during 2011.

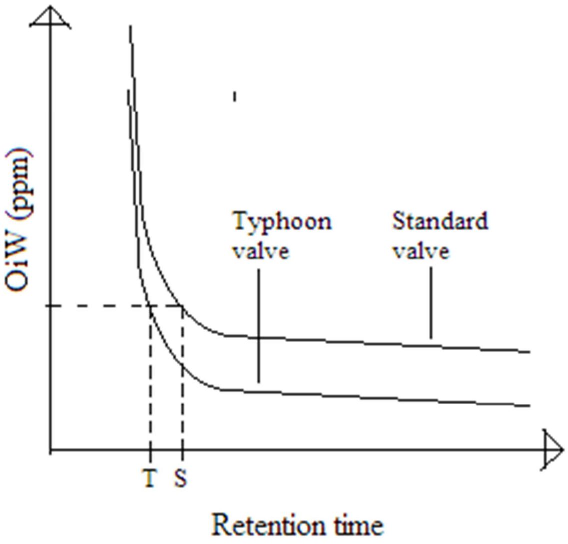

Figure 27. Water quality vs. separator retention time with standard and typhoon valve.

Reduction of OiW concentration which is caused by a faster separation due to the larger oil droplets coming out of the typhoon valve can be used to increase the production rate. The production rate can be increased if the limiting factor in the process is the OiW concentration out of the separator.

5.4.2 Produced water cleaning capacity

The produced water system at Oseberg C is designed to handle 8 000m^3 water per day. During 2011 the system treated 536 688m^3 water (Bratteteig & Dalsrud 2013). This gives an average water production of 1470m^3 per day. September were the month with the highest water production, where 77 236m^3 of water were produced, which gives an average of 2 575m^3 per day. The produced water system is clearly over designed. Also it is common for offshore production facilities to be limited by the topside production system (Finborud 2013), (Biker 2007).

5.4.3 Increase in production

If well production would increase, retention time of the separator will be reduced and more oil will follow the produced water (Figure 27). Reduction in residence time cause larger oil droplets to exit trough the water outlet, which again would cause the D_{50} of the droplets to increase. As long as the flow is within the efficiency plateau (Figure 20) efficiency of the hydrocyclone would not be reduced (Thew 2000). However, the increase of D_{50} would most probably cause hydrocyclone efficiency to increase. But the level of this increase is impossible to predict, and could only be obtained by field tests (Hannisdal 2013). If production would increase, the degasser efficiency would most probably drop because of a reduction in retention time. Effects on the produced water system by increasing production are hard to predict, and will probably wary from field to field. For this case it is just listed as a potential benefit with an unknown effect.

5.5 Summary of results

By replacing standard choke valves with typhoon valves it is possible to reduce the oil emission and the use of flocculants substantially. These results are all based on average values from earlier articles and reports. Basing calculations on average values gives a benefit by lowering the uncertainty of the results. Peak values which otherwise would give a high contribution, either for OiW values and/or efficiency values, are evened out and give a representable value for expected results in the long run.

Hydrocyclones in the process system are assumed to have an efficiency of 75% oil removal. This assumption is based on values given by Statoil and tests conducted at the pre-studies before the pilot test at Oseberg C (Knudsen 2013), (Heitman 2011), (Berntsen 2011). Hydrocyclone results from the pilot test were not used in the calculations, because different cyclone pressure vessels which operated under incomparable conditions were used during the tests (Eidsmo et al. 2012). Since the D_{50} were the same and literature and consultants agrees that OiW concentration does not alter the separation performance, separation efficiency is believed to be the same. The degasser in the process system has been given to have 15% removal efficiency (Knudsen 2013).

There is without doubt a reduction of OiW in the produced water discharge. If standard choke valves had been replaced by typhoon valves at Oseberg C during 2011, Oseberg C would have reduced the amount of oil discharged in the produced water by 4.25 ton. At the same time the amount of flocculants used would be reduced by 30-90 tons. The results from the OiW calculations are summarized in Figure 28.

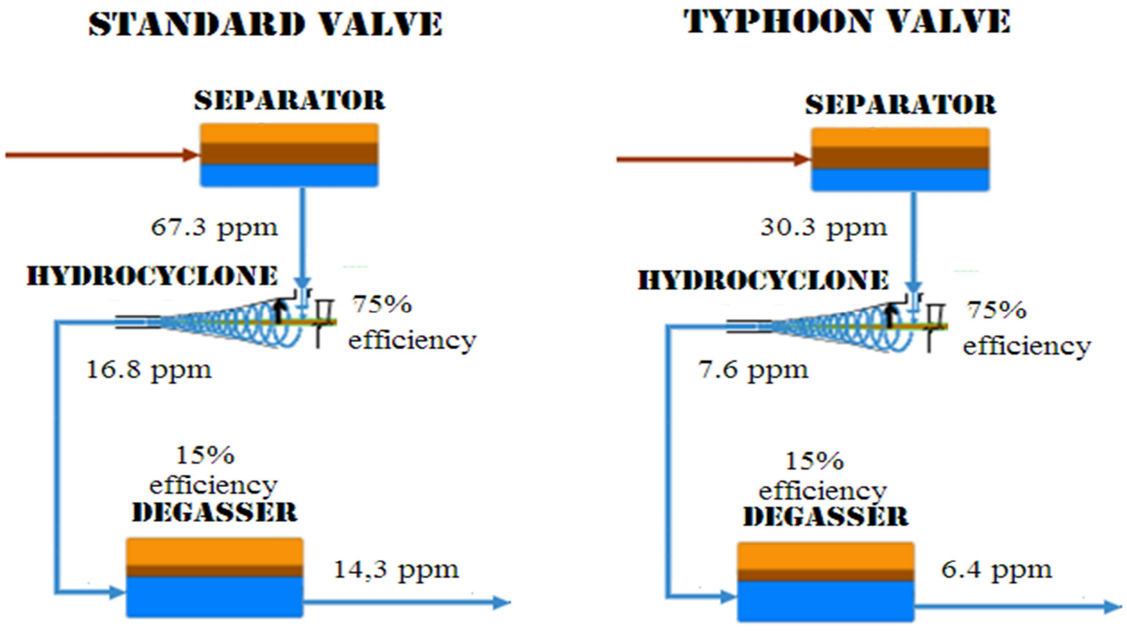

Figure 28. Valve effect on the produced water system.

It is also important to keep in mind that the water cut and thereby also the amount of produced water will increase over time. This will cause the positive effect of the typhoon valve to increase with it, because of the increased amount of water.

5.5.1 Economical relevance

Oseberg C has considered phasing out the old choke valves. For consideration, a standard valve has a purchase cost at about 1 million NOK, while a typhoon valve has a purchase cost at about 1.5 million NOK. The purchase sum for 15 typhoon valves will then be 7.5 million NOK higher than standard valves.

Every year at least 0.3 million NOK will be saved because of less use of flocculants. There will also be a potential profit related to a reduction in transport of chemicals needed. In this work the price for transportation of chemicals are not known. Other economic benefits will be related to a delay of system upgrades. System upgrades which can be avoided are related to installments of additional units in the produced water treatment facility and upgrades of the flocculent injection system. There is also a potential economic benefit by increasing production. But how much the production can be increased is uncertain.

6 CONCLUSION

This thesis is based on the results from the typhoon pilot test at Oseberg C. The work conducted has shown that the typhoon valve gives a significant positive effect on the produced water system. For estimations all choke valves are assumed to be typhoon valves. The most important findings during this work are:

Dispersed oil released with the produced water has been revived to be reduced by 55%. The reduction increases the amount of system upsets the facility can handle before the maximal OiW limit is reached.

When OiW concentrations in the produced water is reduced the need of flocculants are also reduced. A 55 % reduction was estimated, reducing the yearly use of flocculants by 36.7-110 ton. Indirect positive effects can be that an upgrade of the chemical system can be delayed or avoided. Reduction of dispersed oil and the amount of flocculent also reduces the EIF.

The positive effects from the typhoon valves are believed to be lowest at 50% water-cut. From valve tests conducted before this work, the benefits by applying a typhoon valve have increased when water-cuts were different from 50%. During the pilot test at Oseberg C the water-cut were close to 50%. Considering this, the typhoon valve is assumed to at least perform according to the results obtained in this work.

7 REFERENCES

7.1 Articles

Al-Ghamdi, A., Kokal, S. & Aramco, S. (2003): Investigation of Causes of Thigh Emulsions in Gas Oil Separation Plants. Paper SPE 81508, Presented at the Middle East Oil Show & Conference, Bahrain, 5-8 April 2003
DOI: 10.2118/81508-MS

Al-Ghamdi, A. M., Noïk, C. & Dalmazzone, C. (2009): Experimental Investigation of Emulsion Stability in Gas/Oil Separation Plants. SPE Journal, Volume 14, Number 4, pp. 595-605
DOI: 10.2118/109888-PA

Angelidou, C., Keshavarz, E., Richardson M.J. & Jameson G.J. (1977): The Removal of Emulsified Oil Particles from Water by Flotation. Industrial & Engineering Chemistry Process Design and Development, Vol. 16, No. 4, 1977, page 436-441

Arnold, K.E. & Koszola, P.J. (1990): Droplet-Settling vs. Retention-Time Theories for Sizing Oil/Water Separator. SPE paper 16640, SPE Production Engineering, Vol. 5, Nr. 1, page 59-64.
DOI: 10.2118/16640-PA

Arntzen, R. (2001): Gravity separator revamping, PhD study, NTNU, Norway

Belaidi, A. & Thew, M.T. (2003): The Effect of Oil and Gas Content on the Controllability and Separation in a De-Oiling Hydrocyclone. Trans IChemE, Vol. 81, Part A, March, 305-314.

Bennet, F.B. (1988): The removal of oil from wastewater by air flotation: A Review.
DOI: 10.1080/10643388809388348

Bensadok, K., Belkacem, M. & Nezzal G. (2007): Treatment of cutting oil/water emulsion by coupling coagulation and dissolved air flotation. Desalination 206 (2007), page 440-448

Berntsen, J. (2011): Oseberg C – Test av brønn C-12. Mator Prosjekt nr. 10.1105.

Bieker, H. P., Slupphaug, O. & Johansen, T. A. (2007): Real-Time Production Optimization of Oil and Gas Production Systems: A Technology Survey. SPE Production & Operations, Volume 22, Number 4, page 382-391
DOI: 10.2118/99446-PA

Bratteteig, S. & Dahlsrud, A. (2013): Utslipp fra Oseberg – Årsrapport 2011, AU-DPN OE OSE-00083

Choi, M.S. (1990): Prediction of Separator Performance Under Changing Field Conditions. SPE document 20703, Presented at SPE Annual Technical Conference and Exhibition, 23-26 September 1990, New Orleans, Louisiana
DOI: 10.2118/20703-MS

Cline, J.T. (2000): Survey of gas flotation technologies for treatment of oil and grease, Offshore Technol Conf, 7th Annu, Proc;Houston, TX, USA

Colman, D.A., Thew, M.T. & Corney, D.R. (1980): Hydrocyclones for Oil/Water Separation. Proceedings of the International Conference on Hydrocyclones, Cambridge, England, 1-3 October, page 143-165.

Couto, H.J.B., Sant'Anna, G.L. & Massarani, G. (2005): Dissolved air flotation technique for oily effluent treatment, Chemical engineering program/COPPE, Federal University of Rio de Janeiro

Dagle, T.P., Hantz, S.N., Phillips, B. & Janjua, R. (2012): Treating and Releasing Produced Water at the Ultra Deepwater Seabed, OTC paper 23622, presented at the Offshore Technology Conference, 30 April-3 May 2012, Houston, Texas, USA.
DOI: 10.4043/23622-MS

Du, Y., Guan, L. & Liang, H. (2005): Advances of Produced Water Management. Petroleum society paper 2005-060, presented at the Petroleum Society's 6th Canadian International Petroleum Conference (56th Annual Technical Meeting), Calgary, Alberta, Canada, June 7 – 9, 2005.

Eidsmo, G.S., Heitmann, T., Husveg, T. & Kverneland, A.S. (2012): Report from Typhoon Valve Pilot Test on Oseberg C.

Finborud, A., Fucher, M. & Sellman, E. (1999): New Method for Improving Oil Droplet Growth for Separation Enhancment. SPE paper 56643, Presented at the SPE Annual Technical Conference and Exhibition, 3-6 October 1999, Houston, Texas.
DOI: 10.2118/56643-MS

Fjeldly, T. A., Hansen, E. B. & Nilsen, P. J. (2006): Novel Coalescer Technology in First-Stage Separator Enables One-Stage Separation and Heavy-Oil Separation. Paper OTC 18278 Presented at the Offshore Technology Conference, Houston, 1-4 May 2006
DOI: 10.4043/18278-MS

Frankiewicz, T., Lee, C.M. & Juniel, K. (2005): Compact Induced Gas Flotation as an Effective Water Treatment Technology on Deep Water Platforms. Paper OTC 17612, Offshore Technology Conference, 2 May-5 May 2005, Houston, Texas.
DOI: 10.4043/17612-MS

Frankiewicz, T., Lee, J. & Lee, C.M. (2012): Diagnosing and Resolving Chemical and Mechanical Problems in Produced Water Treating Systems, The document is presented as an internet document
(http://ipec.utulsa.edu/Conf2005/Papers/Frankiewicz_Diagnosing_Wtr_Treatment_Problems.pdf)
Accessed 13.05.13
Also exist as a DL online web event
(http://eo2.commpartners.com/users/spe/session.php?id=9338)

Gramme, P.E., Dybdahl, B., Holt, Ø. Friedemann, J.D. & Riise, B. (1999): MTU - The Multi Test Unit for Investigating Offshore Separation Problems and Optimizing the Gas/Oil/Water Separation Process. SPE paper 56847, presented at the SPE Annual Technical Conference and Exhibition, 3-6 October 1999, Houston, Texas.
DOI: 10.2118/56847-MS

Grattoni, C., Moosai, R. & Dawe R.A. (2003): Photographic observations showing spreading and non-spreading of oil on gas bubbles of relevance to gas flotation for oily wastewater cleanup. Physicochemical Engineering Aspects 214 (2003), page 151-155.

Grødal, E.O. & Realff, M.J. (1999): Optimal design of Two- and Three-phase separators: A Mathematical Programing Formulation. SPR paper 56645, presented at the SPE Annual Technical Conference and Exhibition, 3-6 October 1999, Houston, Texas.
DOI: 10.2118/56645-MS

Gomez, C., Caldenty, J., Wang, S., Gomez, L., Moman, R. & Shoham, O. (2001): Oil-Water Separation in Liquid-Liquid Hydrocyclones (LLHC) -Experiment and Modeling, SPE paper 71538, presented at the SPE Annual Technical Conference and Exhibition, 30 September-3 October 2001, New Orleans, Louisiana.
DOI: 10.2118/71538-MS

Hafskjold, B. & Dodge, F.T. (1989): An Improved Design Method for Horizontal Gas/Oil and Oil/Water Separators, SPE pater 19704, presented at the SPE Annual Technical Conference and Exhibition, 8-11 October 1989, San Antonio, Texas

Hafskjold, B., Morrow, T.B., Celius, H.K.B. & Johnson, D.R. (1994): Drop-drop coalescence in oil/water separation. SPE Paper 28536, Presented at the SPE Annual Technical Conference and Exhibition, 25-28 September 1994, New Orleans, Louisiana.
DOI: 10.2118/28536-MS

Hayatdavoudi, A., Howdshell, M., Godeaux, E., Pednekar, N. & Dhumal, V. (2011): Performance Analysis of a Novel Compact Flotation Unit. Journal of Energy Resources Technology, Volume 133/1, 013101
DOI: 10.1115/1.4003497

Heitmann (2011): Test av brønn C-09 på Oseberg C. Mator Prosjekt nr. 10.1105.

Hustad, B.M., Hårvik, A.M.B., Halvorsen, A.M.K. & Waage, J. (2011): Qualification of Production Chemicals – Challenges. Statoil ASA, Internal document

Husveg, T., Bilstad, T., Guinée, P.G.A., Jernsletten, J., Knudsen, B., Nordbø, H.T. (2009 a): A Cyclone-Based Low Shear Valve for Enhanced Oil-Water Separation. OTC paper 20029, presented at the Offshore Technology Conference, 4-7 May 2009, Houston, Texas.
DOI: 10.4043/20029-MS

Husveg, T., Heitmann, T., Kverneland, A.S. & Guinee, P. (2009 b): Full scale testing of Typhoon Valve prototype. Project Doc. 1030.

Hysveg, T. (2007): Operational Control of Deoiling Hydrocyclones and Cyclones for Petroleum Flow Control. PhD thesis, University of Stavanger, Norway.

Husveg, T., Johansen, O. & Bilstad, T. (2007): Operational Control of Hydrocyclones During Variable Produced Water Flow Rates—Frøy Case Study. SPE Production & Operations, Volume 22, Number 3, page 294-300
DOI: 10.2118/100666-PA

Jaworski, A.J. & Meng, G. (2009): On-Line measurement of separation dynamics in primary gas/oil/water separators: Challenges and technical solutions-A review. Journal of Petroleum science and Engineering, 68 (2009), page 47-59.

Khatib, Z. & Verbeek P. (2002): Water to Value - Produced Water Management for Sustainable Field Development of Mature and Green Fields, SPE paper 73853, presented at the SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production, 20-22 March 2002, Kuala Lumpur, Malaysia.
DOI: 10.2118/73853-MS

Kokal, S., Wingrove, M. & Aramco, S. (2000): Emulsion Separation Index: From Laboratory to Field Case Studies. Paper 63165 Presented at the Annual Technical Conference and Exhibition, Dallas, October 2000.
DOI: 10.2118/63165-MS

Lee, D.W, Beteman, J.D. & Owens, N. (2007): Efficiency of Oil/Water Separation Controlled by Gas Bubble Size and Fluid Dynamics within the Separation Vessel, Paper presented at the 17th Annual Produced Water Society Seminar – League City, Texas - 2007

Lee, C. & Frankiewicz, T. (2004): Developing Vertical Column Induced Gas Flotation for Floating Platforms Using Computational Fluid Dynamics. SPE paper 90201, SPE Annual Technical Conference and Exhibition, 26-29 September 2004, Houston, Texas.
DOI: 10.2118/90201-MS

Leech, C.A., Radhakrishnan, S., Hillyer, M.J. & Degner, V.R. (1980): Performance Evaluation of Induced Gas Flotation Machine Trough Mathematical Modeling. Journal of Petroleum Technology, Volume 32, Number 1, page 48-58.
DOI: 10.2118/7246-PA

Lobo, L. & Svereika, A. (2003): Coalescence during emulsification. 2. Role of small molecule surfactants. Journal of colloidal and interface science 2003, Vol. 261 (2), page 498-507.

López-Vazquez, C.M. & Fall, C. (2004): Improvement of a gravity oil separator using designed experiments. Water, Air, and Soil Polution, Volume 157, page 33-52

McLelland, W.G. & Garcia, M. (1998): Investigation into Oil/Water Separation Problems Utilizing RTD Testing and Fluid Properties. SPE document 48994, presented at the SPE Annual Technical Conference and Exhibition, 27-30 September 1998, New Orleans, Louisiana.
DOI: 10.2118/48994-MS

Medrum, N. (1988): Hydrocyclones: A solution to Produced-Water Treatment, SPE 16642, SPE Production Engineering, November, page 669-676.

Michaelsen, J. (2003): Innovative Technology for Ultradeepwater Gravity-Based Separators. OTC Paper 15175, Presented at the Offshore Technology Conference, 5 May-8 May 2003, Houston, Texas,
DOI: 10.4043/15175-MS

Mohammad, A.J.A., Al-Farhan, A.A., Al-Haddad, A.A. & Al-Kholosy, A.S. (2011): The Effect of Suspended Solid Concentration and Oil Droplet Size Distribution on Particle Coalescence and Emulsion Stability. SPE paper 149028, presented at the SPE/DGS Saudi Arabia Section Technical Symposium and Exhibition, 15-18 May 2011, Al-Khobar, Saudi Arabia.
DOI: 10.2118/149028-MS

Moosai, R. & Dawe R.A. (2002): Oily Wastewater Cleanup By Gas Flotation. West Indian Journal of Engineering. Vol. 25, No. 1, page 25-41

Muntinga, J. H. (1998): Study of Turbulent Break-up of Oil Droplets in Choke Valves. Paper SPE 52087-STU Presented at the European Petroleum Conference, Hague, 20-22 October 1998
DOI: 10.2118/52087-STU

Niemi, A.J. (1995): Role of kinetics in modeling and control of flotation plants. Powder Technology, 82 (1995), page 69-77

Nguyen, D., Sadeghi, N. & Houston, C. (2011): Emulsion Characteristics and Novel Demulsifiers for Treating Chemical EOR Induced Emulsions. Paper SPE 143987 Presented at the Enhanced Oil Recovery Conference, Kuala Lumpur, 19-21 July 2011
DOI: 10.2118/143987-MS

OG21 2012, Strategy document, Oil and Gas in the 21st Century, Norway's Technology Strategy for the 21st Century, (http://www.forskningsradet.no/servlet/Satellite?blobcol=urldata&blobheader=application%2Fpdf&blobheadername1=Content-Disposition%3A&blobheadervalue1=+attachment%3B+filename%3D%22OG21strategi2013.pdf%22&blobkey=id&blobtable=MungoBlobs&blobwhere=1274502319567&ssbinary=true) accessed 20.05.13

Oliveira, R.C.G., Gonzalez, G. & Oliveira, J.F. (1999): Interfacial studies on dissolved gas flotation of oil droplets for water purification, Colloids and surfaces, Physicochemical and Engineering Aspects 154, page 127-135

OSPAR Recommendation 2001/1 for the Management of Produced Water from Offshore Installations.

OSPAR Recommendation 2012/5 for a risk-based approach to the Management of Produced Water Discharges from Offshore Installations.

Pal, R. & Masliyah, J. (1990): Oil Recovery from Oil in Water Emulsions Using a Flotation Column. The Canadian Journal of Chemical Engineering, Volume 68, Desember, 1990, page 959-967

Qi, W., Yu, Z., Liu, Y. & Li, Y. (2013): Removal of emulsion oil from oilfield ASP wastewater by internal circulation flotation and kinetic models. Chemical Engineering Science, Vol 91, page 122-129.

Ramstad, K., Rohde, H.C., Dalland, A., Ponomareva, E. & Johansen P. (2012): Flow Assurance in Complex Topside Processes with Subsea Tie-ins and Multiple Fluid Systems. SPE paper 155036, presented at the SPE International Conference on Oilfield Scale, 30-31 May 2012, Aberdeen, UK.
DOI: 10.2118/155036-MS

Santander, M., Rodrigues, R.T. & Rubio, J. (2011): Modified jet flotation in oil (petroleum) emulsion/water separations, Physiochem. Eng. Aspects 375 (2011), 237-244

Seureau, J.J, Aurelle, Y. & Hoyack M.E. (1994): A Three-Phase Separator for removal of Oil and Solids from Produced Water. SPE paper 28535, presented at the proceedings of the SPE 89th Annual Technical Conference and Exhibition, New Orleans, Louisiana, 25-28 September, 193-202.

Sinker, A.B., Humphris, M. & Wayth, N. (1999): Enhanced Deoiling Hydrocyclone Performance without Resorting to Chemicals, SPE paper 56969, presented at the Offshore Europe Oil and Gas Exhibition and Conference, 7-10 September 1999, Aberdeen, United Kingdom.
DOI: 10.2118/56969-MS

Strickland, W.T. (1980): Laboratory Results of Cleaning Produced Water by Gas Flotation, SPE Journal, Volume 20, Number 3, pages 175-190
DOI: 10.2118/7805-PA

Svarovsky, L. (1988): Hydrocyclones, Mining Magazine, August 1988

Sylvester, N.D. & Byeseda, J.J. (1980): Oil/water Separation by Induced-Air Flotation, SPE Journal, Volume 20, Number 6, pages 579-590
DOI: 10.2118/7886-PA

Thew, M.T. (1984): Basic Studies on Hydrocyclones for De-Oiling Water and De-Watering Light Oils. Proceedings of the Ninth Lecture Series on Two-Phase Flow, N.T.H. Trondheim, May, 63-223.

Thew, M. (1986): Hydrocyclone Redesign for Liquid-Liquid Separation. The Chemical Engineer, July/August, 17-23.

Thew, M.T. (2000): Cyclones for Oil/Water Separations, Encyclopedia of Separation Science, Wilson, I.D., Poole, C.F. and Cooke, M. (Eds.), Academic Press, 1480-1490.

van der Zande, M.J. (2000): Droplet break-up in turbulent oil-in-water flow through a restriction. PhD thesis, Delft University, Netherlands.

van der Zande, M. J., Muntinga, J. H. and Broek, W. M. G. T.(1998): Emulsification of Production Fluids in the Choke Valve. SPE Paper 49173, presented in SPE Annual Technical Conference and Exhibition, Louisiana, 27-30 September 1998.
DOI: 10.2118/49173-MS

Welz, M.L.S., Baloyi, N. & Deglon, D.A. (2007): Oil removal from industrial wastewater using flotation in a mechanically agitated flotation cell, Water SA Vol. 33 No. 4 July 2007, page 453-458.

Whitepaper Nr. 26 (2006-07), Stortinget, Norge, Regjeringens miljøpolitikk og rikets miljøtilstand, (http://www.regjeringen.no/nb/dep/md/dok/regpubl/stmeld/2006-2007/Stmeld-nr-26-2006-2007-.html?id=465279) accessed 15.05.13

Whitepaper Nr. 58 (1996-97), Stortinget, Norge, Miljøvernpolitikk for en bærekraftig utvikling. (http://www.regjeringen.no/nb/dep/md/dok/regpubl/stmeld/19961997/st-meld-nr-58_1996-97/9.html?id=191326#E18E42) accessed 15.05.13

Young, G.A. (1987): An Experimental Investigation of the Performance of a 3-in. Hydrocyclone. SPE document 16175, presented at the SPE/IADC Drilling Conference, 15-18 March 1987, New Orleans, Louisiana

Young, G.A.B., Wakley, W.D., Tahhart, D.L., Andrews, S.I. & Worrell, J.R. (1994). Oil-Water Separation Using Hydrocuclones: An Experimental Search for Optimum Dimensions. Journal of Petroleum Science and Engineering, 11, page 37-50

7.2 Web search

Biolin Scientific AS, (Attension.com/interfacial-tension), accessed 10.04.13

Drilling Contractor, (http://www.drillingcontractor.org/refining-the-grip-on-natures-fine-grains-15705) accessed 02.05.13

Energytrendsinsider.com (http://www.energytrendsinsider.com/2012/06/25/how-much-oil-does-the-world-produce/) accessed 01.06.13

Intechopen.com (http://www.intechopen.com/books/computational-fluid-dynamics-technologies-and-applications/numerical-simulation-of-influence-of-changing-a-dam-height-on-liquid-steel-flow-and-behaviour-of-non) accessed 03.06.13

KLIF.no a, Fortsatt behov for å redusere utslippene offshore (http://www.klif.no/no/Aktuelt/Nyheter/2010/April-2010/Fortsatt-behov-for-a-redusere-utslippene-offshore/ Accessed 16.05.13

KLIF.no b, Petroleumsvirksomhetens arbeid med nullutslipp, (http://www.klif.no/publikasjoner/2637/ta2637.pdf) accessed 15.06.13

Lclmg.org, (http://www.lclmg.org/lclmg/Museums/OilMuseumofCanada/BlackGold2/OilHeritage/OilSprings/tabid/208/Default.aspx) accessed 05.06.13

Marietta.edu (http://www.marietta.edu/~mcshaffd/aquatic/sextant/physics.htm) accessed 16.05.13

Newtech.dp.ua (http://newtech.dp.ua/articles/eng/hydrocyclone_history_eng.html) accessed 03.04.13

Offshore.no (http://www.offshore.no/Prosjekter/Olje-felt-informasjon.aspx?navn=OSEBERG) accessed 03.06.13

Offshore-technology webpage. http://www.offshore-technology.com/projects/oseberg/ accessed 13.05.13

Opus webpage, http://www.opus-results.com/technology/process-upgrade/degassers.html accessed 26.04.13

Statoil.no a, information page for the Oseberg field (http://www.statoil.com/no/ouroperations/explorationprod/ncs/oseberg/Pages/default.aspx) accessed 15.05.13

Statoil.no b, information page for Oseberg C (http://www.statoil.com/no/OurOperations/ExplorationProd/ncs/Oseberg/Pages/OsebergC.aspx) accessed 15.05.13

7.3 Consultants

Finborud, Anne: Principal Researcher Process Upstream, Statoil, and lecturer at MET 230 UiS, 2013.

Hannisdal, Andreas: R&D Manager Norway | Separation Systems, FMC Technologies, 2013

Johnsen, Stian: Regional Sales Manager, Scandinavia, (PWSM), M-I SWACO, 2013

Knudsen, Børre: Advisor Process Upstream Production Separation Systems, Statoil, 2013

Kornberg, Terje: Maneger for process systems, Cameron, 2013

Kroknes, Knut: Prin Eng, Statoil, 2011

McLellan, Glen: Director – Strategic Operations, Opus, 2013

Orr, Graeme: Sales manager, VWS Westgarth Ltd, 2013

Ottøy, Magnar: Lead engineer, process technology, Statoil, and lecturer at MET 230 UiS, 2013.

Waage, Jone: Chemical engineer, Statoil, and lecturer at MET 230 UiS, 2013.

Æsøy, Anette: Principal Engineer, Statoil, and lecturer at MET 230 UiS, 2013.

7.4 Books

Barnes, G.T. & Gentle, I.R. (2005): Interfacial Science, an Introduction.

Finnemore, E.J., & Franzini, J.B. (2002): Fluid Mechanics with Engineering Applications. 10th edition, McGraw-Hill.

Selly, R.C. (1998): Elements of Petroleum Geology, Second Edition.