Semester project, EiT

Liquid-Liquid Separation Subsea

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1 PREFACE

The project received at the Subsea crude oil separation village was tilted “Liquid-Liquid separation technology”. The project consisted of the following four tasks: review state-of-the-art separation devices, review existing measurement devices, demonstrate the difference between high- and low-level models, and finally explain what slugging is and how to prevent it. The work was performed in the period from 13th of January to 4th of May.

We would like to use this opportunity to thank our village supervisor Brian Grimes, who provided useful guidance and feedback on our technical report. We would also thank the village facilitators Ingvild Finstad and Philip Jackson who have initiated all our exercises and helped us reflect on the different situations that occurred throughout the course. Finally, we would like to thank our project mentor Christoph Backi who read and gave feedback to our paper in addition to answering any questions we had.
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2 INTRODUCTION

Once a new hydrocarbon field (greenfield) has been discovered, producing oil and gas is a straightforward process. Because oil and gas are naturally confined at high pressure, when a pipe is installed the high pressure will push the fluids up to the platform and so hydrocarbons are produced. However, after the early stage of production (primary recovery) the pressure drops, even though only 5-30% of hydrocarbons was extracted from the reservoir [1]. In order to prolong production of an existing field (brownfield), once the pressure starts to drop, it is necessary to maintain the pressure underground. This process is achieved by injecting pressurized water, gas or both into the reservoir, as shown in figure 1.

![Hydrocarbon reservoir with water (a) and gas (b) injection wells](image)

Figure 1: Hydrocarbon reservoir with water (a) and gas (b) injection wells [1]

Traditionally, offshore functions such as drilling, preparing water or gas for reinjection, liquid–liquid separation, processing the oil and gas before sending it onshore, and cleaning the produced water for disposal into the sea has solely been performed by platforms. Nowadays this trend has been changing [2]. The increasing need of oil and gas energy has forced the search to harsher environments, ultra-deep waters and increased the need for better recovery of the existing fields. Subsea installations are better suited for these new challenges than platforms because in some cases they are safer and more viable, both economically and environmentally. Figure 2 shows the components of (a) a subsea installation with storage vessels (FPSO) attached to a platform, and (b) a conventional platform [1].

![Subsea installation and platform](image)

Figure 2: (a) Subsea installation used in conjunction with a host fixed jacket structure (and an FPSO). Source: Fluor Corporation (2009) (b) floating platform [1]
One of the main advantages of subsea, as compared to solely using platforms, is that it increases and accelerates the production capacity of brownfields by finding out the flow rate-limiting equipment and fixing (or changing) them [3]. This process is called debottlenecking. Because production of a brownfield typically declines due to the decrease in the reservoir pressure, using subsea equipment to boost production by preventing pressure drop saves the companies a lot of money. Notice that debottlenecking is also possible with platforms. In fact, prior to 2008, the recovery factor using platform (secondary recovery) was 7% higher than with subsea wells [3]. However, since then technological advances have greatly reduced and, in some cases, surpassed the gap in the recovery factor between the two methods. According to Toine Hendriks, CDS Engineering’s senior process engineer, subsea technology can exploit an oilfield much deeper and increase recovery up to 10% more from the original reserves [4]. Furthermore, subsea is still attractive due to the following additional advantages:

First, it enables challenging fields to be developed. Some greenfields, due to their location and size, may experience low reservoir pressure or are too small for a profitable platform exploration. Subsea installations connected with a nearby platform may be used to boost the pressure or simply to make production profitable, since no costly platform is installed solely for that given field. In addition, subsea installations bypass the problem of freezing temperatures in harsh environment, such as in the Arctic where topside exploration is difficult due to low temperatures, abrupt weather changes and sea ice. According to the US Geological Survey, 30% of the world’s undiscovered gas and 13% of the world’s undiscovered oil is located in the deep waters of the Arctic. Hence, subsea technologies which enable exploration and development in harsh environments are more important than ever before, now that most of the "easy oil and gas" has been discovered [3, 5].

Second, it reduces investment costs (CAPEX). By utilizing existing infrastructure and without the need of costly topside modifications, companies could save greatly on CAPEX [5].

Finally, health, safety and environment (HSE) are improved. Subsea is invisible at sea level and so it does not disturb marine life and other activities happening there. It is safer than platforms because fewer workers are directly at risk of losing their lives in case of a workplace accident, an un-forecasted storm or other natural disaster [5]. Due to the above advantages and several others, subsea installations have attracted the attention of many companies for about half a century.
2.1 COMPONENTS OF SUBSEA INSTALLATIONS

As figure 2 (a) indicated, current subsea installations serve as support for fixed receiving facilities. They are used as an alternative to satellite or minimum-facility platforms for recovering reserves located beyond the reach of the drillstring. In addition, they can also be used in conjunction with floating production storage vessels (FPS), and floating production storage and offloading vessels (FPSO).

For any active treatment and handling of hydrocarbons at the seabed, today’s technology allows three types of subsea installations, namely: boosting (or pumping), separation and compression.

Figure 3: Subsea systems worldwide as of Feb 2015 (source: INTECSEA, Worley Parsons Group)

Figure 3 shows that many and different types of subsea systems are being installed, tested, conceptualized and/or operated in all continents. Notice that more than one type of subsea installation may be deployed in the same field, depending on its need. For example, Perdido platform in Brazil, and Pazpflor in Angola, have subsea separation and boosting currently installed and operating on them, whereas at Gullfaks in the Norwegian Sea, there is only compression. As the map of figure 3 illustrates, each one of the three existing subsea system may operate alone or combined with the others. In fact, Statoil, the leading company in subsea development, aims to take subsea technology at longer, deeper and colder environment by developing a subsea factory – a subsea installation 100% independent of the platform [6].
A subsea factory will function as a platform at the seabed by integrating boosting, separation, compression and storage of hydrocarbons, as indicated in figure 4. Boosting installations enhance produced fluids (in the liquid or multiphase state) by allowing better pressure management of the reservoir. This leads to an extended tail-end production of the reservoir as well as the reservoir having a higher, longer and earlier plateau production. Separators separate oil or gas from water or other substances and reinject the water into the reservoir in order to boost production. Compressors compress and cool the gas so that it could be either stored, for sale, or reinjected into the reservoir [3]. The magic of a subsea factory is that all the three components would work together instead of simply having a combination of one or two as it happens today [6]. In this work we focus only on subsea separation, in particular, on liquid-liquid separation.

### 2.2 THE NEED FOR SUBSEA SEPARATION

When oil is produced, it also produces water, sand, drilling fluids and drill cuttings. These substances, which are unintentionally produced during oil production, are called production waste, or simply waste. Produced water is the most critical of the wastes because it is produced at a very high quantity. During a lifetime of a reservoir, on average, four barrels of water are produced for each barrel of oil [1]. This trend increases even more as we move into more challenging fields, as indicated by figure 5(b). As the pressure of a typical brownfield decreases with time, the waste increases. For a subsea well, this scenario creates problems in the topside receiving facilities because they are not designed to handle increasing amounts of water. In addition, the extra water leads to further pressure drop in the flow lines and risers from the well to topside [5]. This will eventually stop the production or drop the pressure to an unprofitable level of production. Subsea separation is used as one way of fixing this problem, shown in figure [295x41]
Figure 5: (a) Diagram of a subsea separator system [7] (b) Producible water per barrel [1]

As the diagram in figure 5(a) shows, subsea separators prevent the producible waste from going directly to topside by separating the gas and water from the oil, and sending them separately to the platform. While subsea separators separate all the waste from the oil or gas from oil, liquid-liquid separators deal only with water-oil separation. By separating the water from oil before sending topside, liquid-liquid separators overcome the problem of pressure drop (caused by excess water in the topside) and emulsion (caused by the presence of water in oil). This process leads to positive pressure balance and increased production. In addition, the produced water that has been separated can be used as water injection, as shown in figure 1 (a), and further increase pressure in the reservoir. Hence, due to its importance, many subsea separators have been implemented around the world, as shown on table in figure 6.

Besides increased production, subsea separators also enable companies to comply with environmental requirements regarding disposal of producible waste, including water. Produced water is composed by elements which can greatly harm the environment, hence discharge of such water into the ocean are becoming increasingly stricter. Many regulations such as the Baltic Sea Convention and Helcom, the Barcelona Convention (on the Mediterranean Sea), the Kuwait Convention (on the Red Sea), the OSPRARCOM (on the North Sea), the US regulations for the Gulf of Mexico, among others set stringent rules about the maximum concentration of oil in water that could be discharged into the sea daily and the monthly average [1]. Therefore, due to its economic and environmental advantages, subsea separators constitute a vital component for any subsea installation.
Separation properties, components and basics

Separating oil and water may seem as an easy process, but the fact is that this is very complex and hard. Crude oil consists of a huge amounts of different hydrocarbon molecules which affect the separation. There is a wide variation in properties from the lightest crude oil to the heavy asphaltic crudes. The composition of crude oil is complex and it is not possible to characterize them by either molecular analysis or elemental analysis. Therefore to characterize them, hydrocarbon group type analysis called SARA separation is employed [8]. This type of separation analysis divides the crude oil in four main classes based on differences in solubility and polarity. The main SARA fractions are

- Saturates(S): These are the non-polar hydrocarbons without the double bonds, but it includes normal alkanes, branched alkanes, naphthenes. Wax is the subclass of saturates.

- Aromatics(A): The term aromatics basically refer to benzene rings and its structural derivatives.

- Resins(R): These comprise of polar molecules which contain heteroatoms like Nitrogen, Sulphur and Oxygen. The hydrocarbon ratio in Resin is higher in comparison to the asphaltenes. The structure of Resins is similar to that of the Asphaltenes, but lesser molecular weight.

- Asphaltenes(A): They are defined in the solubility class and also contain polar groups and acidic and basic groups. These are polycyclic molecules that are in the shape of discs and tend to form stacked aggregates. Asphaltenes precipitates in pentane, hexane or heptane. This precipitate is soluble in toluene and benzene.
**Emulsions**

To understand separation, it is necessary to understand the emulsions. An emulsion is a dispersion of one liquid in another immiscible liquid. The phase which is in droplet form is the dispersed phase, and the phase which the droplets are present is called the continuous phase. There can either be water-in-oil or oil-in-water emulsions. An oil-in-water emulsion is easier to separate [9]. The amount of oil and water in the phases can be very different in the separation systems. Even though it only looks like there is one phase in the separation process, it usually consists of multiple emulsions, which are more complex, which makes it harder to separate. For instance, a water-in-oil-in-water emulsion consists of oil droplets dispersed in the water phase, and this in turn is dispersed in continuous water phase. These are called double emulsions, which are unstable and hence they quickly form single emulsions [10].

The emulsions from the oil field contain oil, water and emulsifying agents. The emulsifying agents include the surface active agents and finely divided solids. Surface active agents are more commonly known as surfactants. The surfactants have a hydrophobic part that has a strong affinity for oil particles and the hydrophillic part that has a strong affinity for water particles. These surfactants tend to accumulate at the oil water interface forming interfacial films which further leads to the lowering of the interfacial tensions. Asphaltenes, resins, oil soluble organic acids and bases are the emulsifiers in the crude that occur naturally. Heavy crude oils contain large quantities of asphaltenes and it is their surface active nature which makes them better emulsifiers than the other naturally occurring emulsifiers present in the crude oil [11].

![Figure 7: The picture to the left is W/O and the picture to the right is O/W emulsions](image)

![Figure 8: Water-in-oil-in-water emulsion](image)

The first step of separation is flocculation. Droplets of oil gather together, and if the interfacial film is weak, the flocculation force may be sufficient to break the film and cause coalescence, which is basically when droplets melt together and form a bigger droplet. The amount of the different hydrocarbon components in the crude oil, amount of water etc, will effect the flocculation and
coalescence process and thereby the separation. So there are many different factors and properties which affects the separation, which makes it difficult to separate efficiently.

![Figure 9: Sketch that shows the flocculation process](image)

![Figure 10: Sketch that shows the coalescence process](image)

**The separation concept**

Separation is a very important aspect of oil processing. First of all, the water that is disposed back to the sea after production needs to have a limited amount of oil content in it because of environmental aspects. Other important factors that make separation important is the storage capacity on the offshore facilities. The storage capacity is limited on the platforms, and therefore it is better to get rid of the water to get more storage space available. When the oil is carried onshore by vessels, it is also more ideal to reduce the water content because the value lies in the oil, not the water. Subsea separation is a modern and new way of separation because the separator is placed on the seabed.

There are some important points that makes subsea separation attractive. One of them is the space limitation on the platforms. The troll pilot, which was the world’s first subsea water separation and injection system, was placed subsea because of the space limitations on the platform of Troll C. The limited platform space would make expansions due to separation systems difficult and costly. Other beneficial factors with subsea separation is the possibility of water injection in to the reservoir without transporting the water to the platform. This could reduce the required pump capacity and pipe size and thereby costs. The separation process is the same, independent of the separator being installed topside or subsea.

The separation is initiated by a force, either by natural gravity force or by a centrifugal force created by rotation. The principle is basically the same, but the methods are different. The centrifugal force applied in a hydrocyclone can be up to 1000 times bigger than the gravitational force in a gravity separator. The details and differences between the two separation methods
will be discussed in section 3.2 and 3.4. The separation process is mainly the same for different reservoirs and wells, but details may vary depending on the situation, like the properties of the oil, amount of water, temperature etc. The separation time, which is a very important aspect in separation, can vary depending on the system. There are many factors that influence the separation time. The oil (droplet size, viscosity etc) and water properties for instance, are different in each reservoir. This can be seen from figure 12, which shows the separation time for different crude oils with 20 % water cut. It can be observed that the yellow line which indicates the condensate has less resins and asphaltenes when compared to light crude indicated by the green line and the heavy crude indicated by the red line in the figure which has lot more resins and asphaltenes. An important property is how much water and oil it is in the emulsions. The emulsions can either be water-in-oil or oil-in-water emulsions. The oil-in-water emulsion is easier to separate, therefore water is sometimes added in the separating process [12] [13] [9].

Figure 11: The oil in water phase is easier to separate

Figure 12: Separation time depends on factors like the oil properties

To have a successful and efficient separation, different chemicals, inhibitors and methods are available for use. A short summary of the most used methods are described below [9]:

1. Foam inhibitors decreases the foam activity. When the oil flows in to the separator, foam usually appears because of gas mixed in the phases, which is unwanted because it makes it harder to separate the oil-water phase and harder to measure the oil-water level in the separator.

2. Demulsifiers (emulsion inhibitor) help displacing the oil from the water by decreasing the surface tension between water and oil. The demulsifiers compete with the natural surfactants in the oil, and displaces them from the oil-water interface as seen in figure 13.
These demulsifiers mainly attack the resins and the asphaltenes. The disjoining pressure decreases, which makes the distance dependence of interaction smaller, and thereby it is easier to separate.

3. Coalescence (Droplets melting together):
   - increasing the temperature lowers the viscosity which helps the separation and therefore a quicker sedimentation which is further discussed in section 3.2.
   - increasing collision frequency by adding water and increasing the temperature.

4. How much chemicals, temperature increase, water etc. that need to be added, differs depending on the system. It depends on the oil and water properties, which is usually very different in each reservoir. The properties used for separator design and sizing are:
   - Physical properties and also the chemical properties of crude oil and water
   - Laboratory and flow loop test results (the time the droplets have for settling and sedimentation)

Figure 13: Emulsifiers separating the water-oil phase
3.1 EQUATIONS

As mentioned, the separation is initiated by either the gravitational or a centrifugal force depending on the separator. In case of the gravity separator, the relation between the active force and the density of the fluids is given by the gravitational buoyancy force formula:

\[ F_g = V_d(\rho_d - \rho)g \]  

Here \( \rho_d \) is the density of the droplet and \( V_d \) is its volume, dispersed in a liquid with density \( \rho \). Where \( g \) is the gravitational acceleration, which will be the case in a gravity separator. If the separation is performed by cyclones or swirl flow the force is given by replacing \( g \) in formula (1) with the centrifugal acceleration \( a \).

\[ F_c = V_d(\rho_d - \rho)a \]  

The frictional force acting on an object moving through a fluid, in this case an oil droplet, counteracting the buoyancy force, is given by:

\[ F_d = -\frac{1}{2}C_dA_d|v||v| \]  

Where \( C_d \) is the drag coefficient, \( A_d \) is the reference area of the object and \( v \) is the relative velocity of the object to the fluid.

When oil and water is mixed and only affected by gravity, the water droplets will slowly move downwards while the oil droplets go upwards. The speed at which this is happening is given by Stoke’s law:

\[ u = \frac{gd^2(\rho_{droplet} - \rho_{fluid})}{18\mu} \]  

Here \( u \) is the velocity \((m/s)\), \( g \) gravitational acceleration \((m/s^2)\), \( d \) the droplet diameter \((m)\), \( \rho_{droplet} \) is the mass density of the droplets \((kg/m^3)\), \( \rho_{fluid} \) the mass density of the liquid \((kg/m^3)\) and \( \mu \) is the dynamic viscosity \((kg/m \cdot s)\).

The relationship of the distance between a swirl element and the outflow section, and the residence time for an oil droplet is given by the following equation:

\[ t = \frac{\pi(R^2 - R_i^2)L}{(1 - FS)q_{in}} \]  

Here \( t \) is the residence time, \( R \) and \( R_i \) are the radii of the HPO and LPO respectively, \( q_{in} \) is the volumetric flow rate at the inlet, \( FS \) is the flow split and \( L \) is the distance between the swirl element and the outflow section. The importance of this relationship is discussed in chapter 3.3 \[14\] .
3.2 GRAVITY SEPARATORS

To this day, separation at the seafloor is still a method that is under development, and so far three liquid-liquid separators are deployed at the seafloor, where two of them are gravity separators. The concept of the gravity separators is based on exploiting the density difference between two liquids, as they are naturally separated by gravity. The separators could either be vertical or horizontal. A vertical separator could be used to save space on a topside facility, and is mostly used to separate gas/liquid. The horizontal gravity separator is the most common separator for liquid-liquid separation, and this is the type of separator that is installed subsea so far. A multiphase flow with oil, water and sometimes gas is flowing through the inlet into the separator. It is here divided into two layers: Water with the highest density will drop to the bottom, oil with a lower density will flow on top of the water layer, with a foam layer created by the gas, lying above the oil. The multiphase flow is eventually stopped by a barrier, like a wall (weir), where oil which flows on top of the water, will flow over the barrier. This is the basic principle of a gravity separator.

![Figure 14: Three phase gravity separator separating gas, oil and water](image)

The main principle of the separation is the droplets distribution based on density. Oil droplets will move upwards in the water, and when hitting the interface between oil and water, it is called creaming, while the water drops will move downwards in oil, hitting the interface which is called sedimentation. The movement of the droplets is called settling. The settling velocity can be found by Stoke’s law, equation (4).

![Figure 15](image)

**Figure 15**
Oil droplet in movement, called settling velocity

![Figure 16](image)

**Figure 16**
Creaming and sedimentation. Oil is yellow and water is blue
Gravity separators are the most common separator type in the offshore industry, and is the first separator type to be used subsea. The biggest difference between subsea separators and topside separators is the size and robustness. The subsea separators need to withstand external and internal pressures, harsh environment etc, and need to be compact. The differences in internal pressures in topside and subsea, is that a subsea separator does not have the same opportunity to flare the gas as you can do topside. The lack of this opportunity can cause high internal pressure, and therefore compact and robust separators are very important. Another usual difference is that on topside, cooling of the liquid is needed before separation, this is not the case subsea. Subsea separators can also be used to clean out the gas in the inlet to reduce the size. Compact separators will reduce size, weight and also cost. Lighter separators allow the system retrieval, maintenance and installation process without the use of heavy-lift vessels, which reduces the cost significantly. In addition, the separators can be tested as an integrated system on the surface prior to installation. This will increase the reliability. These are the three following subsea separator installations:


**Troll Pilot Separator:** This is a three-phase gravitational separator. This means that it separates water and oil, but also the gas. For the oil-water separation, two weir plates are installed at the end of the separator. The inlet has a cyclonic device that slows down the incoming flow and also decreases the amount of emulsion. This cyclonic inlet is also removing gas bubbles, and then transporting the gas through a separate gas line. This minimizes the separator size [9].

![Figure 17: (a) Troll separator, (b) Hydraulic scheme](image)

**Tordis Separator:** This is also a three-phase gravity separator with the cyclonic inlet device. The separator has about 30-40% water in the oil and the produced water which is separated contains 500 ppm of oil (30 ppm is the limit, before it can be released in the sea) and is pumped back to the Utsira reservoir. There is a lot of sand production in this case, and a sand removal system which contains flushing systems with nozzles are installed to remove the sand. This separator has very limited maintenance access. One important difference from this separator compared with all other separators, is the missing weir plate. This separator does not use a plate to separate the oil and water, but has simply an outlet at the top in the oil region, and one in the water region [9] [15].
Figure 18: Similarities and differences between Tordis Separation and topside separation. The picture placed highest is topside.

Figure 19: Tordis gravity separator

**Marlin separator:** This separator consists of a pipe separator with hydrocyclones. The hydrocyclone separator is the most compact, but also the least robust. The pipe separator is based on the idea that the separation takes place from the start both in the well and in the flowline, and the pipe is curled in a template, to increase the sedimentation process. The pipe separator is very efficient for oil-water separation. It works in the same way as a conventional separator, but the small pipes can withstand high external pressures and can be used in very deep water. The small diameter also gives a short sedimentation time. The hydrocyclones then separates the remaining water from the oil [9] [15].

Figure 20: Marlin Separator, pipe separator with cyclones
3.3 SWIRL SEPARATORS

The separators used subsea today are only gravity separators, but they have some drawbacks. Mainly the large size and weight that makes them unattractive to install at small wells or at remote locations caused by ship limitations. This creates a need in the industry for solutions that use small separators, like the swirl separator. The benefits of using a swirl separator are lower investment cost and easier installation because they weigh less. They can also be installed directly in the pipes of the flow, eliminating the need to build dedicated structures for the separation. With the benefits of a small separator, comes new challenges to control and design due to short residence time, and optimization becomes more vital [16].

Even though it may be better, the “compact solution” is yet to be used subsea mainly because of the lack of operational experience even topside. This could lead to unforeseen problems for the first commercial use of this technology that the oil companies does not want to risk, which is why most work done concerning the swirl separators today are research related [17].

What is a swirl separator?

A typical swirl separator consists of three main parts; the swirl element, the cylindrical pipe where the swirl element is placed and the outflow section. The swirl element is a bullet shaped part with vanes attached to it, as shown in figure (21). The vanes deflect the passing fluid creating a swirling flow behind the element. The angle between the stream and the vanes affect how strong the swirling flow will become. The cylindrical pipe in which the swirl elements is placed in can be a flow line or an independent pipe just for separation, making it very versatile to where separation could be done. The swirling flow caused by the element will make the oil to be concentrated in the middle of the pipe while the water is pressed out to the sides. Shortly after the swirl element, comes the outflow section where the heavy and light phases are collected in their respective flow lines, also called HPO (Heavy Phase Outlet) and LPO (Light Phase Outlet), figure 22.

![Figure 21: A swirl element placed inside a pipe.](image)

How does it work?

The swirling flow made by the separator forces the oil to concentrate in the middle of the pipe. The two factors that contribute to this, are the centrifugal force and the difference in density between oil and water.

This can be seen by inserting values in equations (2) and (3) which will yield the forces acting on the oil droplets in a stream. The force acting on the oil droplets will have a magnitude and direction, assuming it is greater than the friction \( F_c > F_d \) it will cause the oil to concentrate.
in the middle of the pipe as in figure 22.

An important parameter for swirl separators is the distance between the swirl element and the outflow section, as all oil droplets will have a residence time. The distance must therefore be shorter than the residence time, allowing the droplets to pass through the LPO which is located in the center of the pipe. The distance can however be too short in some cases. For instance, if the amount of oil that has travelled the necessary distance is greater than the flow rate through the LPO, the oil core will simply grow wider than the radius of the inner pipe \( R_i \) and the residual oil will exit through the HPO. The relationship between the distance and residence time for an oil droplet can be seen in equation (5).

Figure 22: Mixed flow before the swirl element, separation occurring after passing the element. Further downstream there is a LPO in the middle and a HPO behind the LPO.

Separation by swirling flow is successfully used for separation of solids from either gas or liquids. However, the use of swirl separators for liquid-liquid separation has proven to be more difficult, because of the much smaller difference in density between the phases and high volume fraction of the dispersed phase [18]. Research of the effectiveness is therefore important to find a good design for the separator.

Research

Most work done concerning the liquid-liquid swirl separators is focused on measuring the separation effectiveness and optimizing it. For this purpose, good models that describe the flow behavior are needed. Having a model that correlates well with the real world will save a lot of work by allowing a computer to calculate optimal parameters like LPO and HPO diameter, vane angle and distance between swirl element and LPO for a given set of inlet conditions. Good separation models can also be applied under operating conditions for consistent monitoring, providing estimates of the outlet stream composition.

A good model should be accurate, yet simple to avoid high computational cost and time. It is therefore important to identify what the model shows and try to express it as simple and realistic as possible.

Work done by two people from different universities are compared further down, to see if there were any differences between their results using different models. The first work is done by Preben Fürst Tyvold at the Norwegian University of Science and Technology. He made a model describing separation efficiency and compared it to experimental data given by Van Campen to see how good it corresponds. The model showed good fit with experimental data but had deviations for some operation conditions.

In the model, he assumed two axial velocity profiles one inner and one outer. Tangential velocity is also divided into two profiles, one inner solid body rotation and one outer free vortex.

He then found the inlet position of the oil droplet that would cause it to exit through the inner
pipe (LPO). An assumption was made, that all droplets entering at a specific area would exit through the LPO, and all droplets entering outside of that area would exit through the HPO. He also added re-entrainment of the fluids to the formula.

After making the model, he ran several simulations and found out the following: the modeled separation performance is sensitive to changes in flow rate, centrifugal forces, droplet breakup and residence time. Separation performance can therefore be optimized by finding an optimal balance between those factors for given inlet and geometry conditions. The optimal distance between the swirl element and the LPO is governed by the residence time of an oil droplet.

The simulated and experimental values show good agreement for low oil cut values, the accuracy decreases for oil cut equal to or higher than 0.45, that was most likely because part of the liquid changes from oil-in-water to water-in-oil emulsion. Increasing feed rate decreases performance and a stronger swirl flow is achieved, but the droplet breakup is increased. For the pipe diameter Preben used, the model was in best agreement with the experimental data for the following conditions:

- Inlet oil cut between 0.2 and 0.45
- Flow rates between 10 and 20 $m^3h^{-1}$

Because the swirl separator is not effective for high oil cuts, it should be used in a combination with other separators like the gravity separator for increased performance. Preben in his design, also worked on a gravity separator initially for coarse separation and two swirl separators after it for finer separation of oil in water and water in oil [14].

Van Campen made an experimental setup and compared the measurements with the simulation models he made. In his work, he used a so-called Euler-Euler model combined with separate continuity and momentum equations for both phases to describe the two-phase flow. He tested the model with two forms of drag laws and compared the results with experimental data. The drag laws used were the Schiller-Naumann and the Ishii-Zuber, with the Schiller-Naumann correlation not taking into account hindrance effect other droplets have on the movement of a droplet, while Ishii-Zuber is doing so.

He defined the separation efficiency by measuring the amount of oil that entered the inlet and compared it with the amount of oil that left through the LPO. The oil cut was set to 0.25 at the inlet, representing a high watercut wellstream. By applying the Schiller-Naumann drag relation, a separation efficiency of 98% was achieved and by applying the Ishii-Zuber drag relation, a separation efficiency of 89% was achieved. The experimental result indicated a separation efficiency of 65%, it appears therefore that in both cases the models overestimated the results. The main reason for this was determined to be the effect of turbulence on segregation of the oil, which was not taken into account. The highest axial velocity was observed when the Schiller-Naumann model was used, which also yielded the highest separation. He also found out that the oil volume fraction of the "pure" oil region in the centre of the flow could only reach 80%. The reason for this was high mixture viscosity caused by the high oil cut, for instance at an oil volume fraction of 0.80 the mixture viscosity was 40 times higher than the water viscosity which prevented further separation [18].
The conclusion of both works was that further research is needed to understand the flow better
and improve on the separation models. If however a model that was good enough is developed
it is important to have instrumentation that can feed the input data for monitoring purposes,
different kind of monitoring devices are discussed in chapter 5. Control of this separator under
operating conditions may be virtually impossible as most elements are fixed. This makes it
more important to have good models which can be used to design the optimal system before
installation.

In the future, when technology allows it, a swirl separation system could be designed where it is
possible to control the vane angle and the distance between the element and the outflow section.
This would allow the separator to be used under more operating conditions where the flow and
oil cut changes with time, giving it a longer lifespan. An illustration of how we think it may be
done is shown in figure 23.

![Figure 23: The futuristic swirl separation system](image)

In the illustration, the bullet could be attached to the rails in point B and moved to a desired
location by two hydraulic motors in point A. Power delivered to the motors from a subsea factory
could be passed through point A and into the rails going into the bullet though point B. An
electric motor could be inside the bullet controlling the vane angle.
3.4 CYCLONE SEPARATORS

In the past, oil-water-gas separation technology has been based on conventional vessel type separators which are bulky, heavy and expensive. As the petroleum industry is currently more focused on producing hydrocarbons from offshore fields keeping in mind the economic challenges to reduce the production costs, the research interest is currently more inclined towards compact separation using low weight, low cost and efficient separators.

**Cyclone separator**

Cyclones are devices used to separate dispersed phase from a continuous phase based on centrifugal forces. There are three types of cyclone separators

a) Conical Liquid Hydrocyclones (LLHC)

b) Liquid Liquid Cylindrical Cyclones (LLCC)

c) Gas Liquid Cylindrical Cyclones (GLCC)

The main difference between the cylindrical cyclone separator (LLCC) and the conical hydrocyclone separator (LLHC) lies in the design or geometry, since LLCC has a cylindrical body and the LLHC has a cylindrical top portion and it is tapered down to a conical structure.

Most of the studies on liquid-liquid separation have been focused on conical liquid hydrocyclones (LLHC). Studies on the use of cylindrical hydrocyclones for the liquid-liquid separation have been hindered because at high velocities they perform as mixers rather than separators. However, it is said that while operating at moderate velocities, the cylindrical hydrocyclone can be used to perform as a free water knockout system [19].

**Principle of Cyclonic Separation**

A cyclone separator is a vertical pipe with a tangential/horizontal inlet and two outlets, one at the top and other at the bottom, which uses the centrifugal separation technology. The immiscible mixture of two liquids flow through the inlet into the cyclone separator. Therefore a strong swirling flow field is formed causing the lighter phase to migrate to the centre line and the heavier phase towards the wall. Due to the density difference, the denser component tends to be accumulated near the wall and spirals down the bottom outlet while the lighter component flows to the core region of the cylindrical cyclone and leaves through the top outlet.

In the case of oil water separation, produced water from the gravity separators enters the cyclonic separator tangentially and flows down the conical vortex. The oil droplets which have a lower density than the water, flow into the centre of the separator and are removed through the overflow, while the treated water flows out through the underflow.

**Performance of a cyclonic separation**

For the studies on cyclone separators, two parameters have been used to define the total separation efficiency, namely the flow split ratio and the pressure differential ratio.
The flow Split Ratio is defined as the ratio of the underflow rate to the inlet flow rate.

\[
SR = \left(\frac{Q_{\text{underflow}}}{Q_{\text{inlet}}}\right) \times 100
\]

Optimal split ratio: This is defined as a particular split, wherein maximum free water knockout is obtained.

Pressure Differential Ratio: This is defined as the ratio of overflow to underflow pressure drop.

**Liquid Liquid Cylindrical Cyclone**

![Diagram of LLCC](image)

**Figure 24: LLCC**

LLCC has a horizontal inlet and two outlets for the separation of oil and water. There were several experimental studies on LLCC by the University of Tulsa. During the experimental study of the LLCC by R. Mathiravedu et.al(2001), four patterns were observed at the horizontal inlet. These patterns depend on the combination of oil and water flow rates, pipe diameter and fluid properties. The different flow patterns are Stratified flow pattern, Oil in water dispersion and water layer, double oil in dispersion, and oil in water dispersion have been summarised in the table 1.

**Table 1: Inlet Flow Patterns**

<table>
<thead>
<tr>
<th>Sl.No</th>
<th>Flow Pattern</th>
<th>Superficial water velocity ( (v_{sw}) )</th>
<th>Superficial Oil velocity ( (v_{so}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stratified Flow</td>
<td>( v_{sw} &lt; 0.2 )</td>
<td>( v_{so} &lt; 0.1 )</td>
</tr>
<tr>
<td>2</td>
<td>Oil in water dispersion and water layer</td>
<td>( 0.2 &lt; v_{sw} &lt; 0.8 )</td>
<td>( v_{so} &lt; 0.2 )</td>
</tr>
<tr>
<td>3</td>
<td>Double oil in water dispersion</td>
<td>( 0.2 &lt; v_{sw} &lt; 0.8 )</td>
<td>( v_{so} &gt; 0.2 )</td>
</tr>
<tr>
<td>4</td>
<td>Oil in water dispersion</td>
<td>( v_{sw} &gt; 0.8 )</td>
<td>-</td>
</tr>
</tbody>
</table>

The experiments on LLCC were carried out by Mathiravedu et.al(2001) for several water dominated runs, i.e the superficial water velocity being more than the superficial oil velocity \( (v_{sw} > v_{so}) \). The experiments reveal that there is no complete separation of oil and water. Results also
say that at low split ratios, the effluent in the underflow is clean water and at some split ratio, the oil droplets appear in the underflow. For an optimal split ratio, the water stream at the underflow has 100% watercut. This optimal water-cut depends on the various inlet flow patterns, oil content and the velocity of the mixture. The results were plotted as watercut underflow vs the split ratio and it was concluded that the better separation efficiency is achieved for the stratified flow and double oil in water dispersion flow pattern [19].

Conical Liquid Hydrocyclones

This type of hydrocyclone consists of cylindrical geometry at the top and conical geometry at the bottom. The cylindrical section is important to avoid a high shear region downstream of the entry and also helps to reduce the head loss. Although it is very important to have the cylindrical part, its length has to be as short as possible. It needs to be designed carefully, because an excessive length leads to weakening of the swirling flow due to wall frictional effects. To avoid the swirl weakening, the cyclone separator usually has a conical lower part to maintain the swirl intensity and hence a stronger centrifugal separation [20].

For the experimentation purpose, the tests were carried out using different inlet geometries. The main aim of different inlet geometries was to inject the fluid at a higher tangential velocity, which avoids rupture of the droplets [21]. The different geometries at the inlet include rectangular inlets, circular inlets, single and the twin inlets.

Gas Liquid Cylindrical Cyclone

This is used as a gas liquid separation device which is a simple, compact and a low cost separator. It is a vertical pipe with a tangential inlet and two outlets as shown in the figure 26. The three phase mixture enters the GLCC at the tangential inlet, and the lighter gas moves through the top and the water oil mixture exits the bottom of the separator as shown in the figure below. The separation in the GLCC is based on centrifugal and gravity effects.
University of Tulsa has carried out studies to extend their research on cylindrical cyclone to three phase gas oil water separation as shown in figure 27 based on the integration of GLCC and LLCC to separate the two phase mixture from the bottom of the GLCC [22].

The GLCC has several installations (more than 1000) mainly onshore, and a lot of study on this has been done by University of Tulsa [23]. GLCC being compact, performance under the slugging environment is expected to be hard. Consequently, a slug damper system was developed to provide volume for liquid accumulation.

**Subsea Applications**

Saipem has partnered with Veolia to develop subsea water treatment solutions for the deepwater applications. One of the major shortcomings of the large diameter vessels used on Troll and Tordis was a very thick wall which required to sustain high pressure. Therefore, Saipem is currently developing two bulk liquid separation systems to fit deepwater requirements to overcome the shortcoming [24].

The first system is called SpoolSep. Here, the fluid is divided into several spools working in
parallel. The separation efficiency is increased based on the spool lengths, because the lengths provide long residence time [24]. The second system is called the 3C-Cyclone. This cyclone separator has been designed specifically for subsea applications. The advantages of this system is that it works over a large range of water cuts and there is no requirement of any fast acting control device. Compliance to the variations in the inlet flow rate and watercuts, is achieved by innovative cyclone geometry and the pressure regulating vessel. Experiments have been performed with two synthetic oils and salt water under different flow conditions. The test results have shown very good separation performance at the outlet of the 3C-Cyclone system.

Addition of cyclonic deoiler helps to reduce the concentration of oil in water to less than 100 ppm for a few reservoirs [24]. If the oil at the outlet better than 100 ppm is to be achieved, a polishing stage is to be added. There are two solutions described below.

The first solution is to use the floatation unit. Induced Gas floatation (IGF) equipment is commonly used to remove oil further, when the performance of the hydrocyclone is not capable to meet the injection requirements of the reservoir or the discharge requirements by the regulatory board. There have been conventional IGF’s in use for many years, but due to their high retention time and huge weight led to the development of Compact Floatation Unit (CFU). Most CFU’s made use of recirculation pumps to drive eductors, and hence their use in subsea applications was not appropriate. To overcome this problem, the VWSCophasë™ CFU came up with the novel solution of LoHead™ eductors allowing the floatation unit to operate without the need for the power and a very minimal requirement of process control, and hence it makes it a very good prospect for subsea application.

The second solution for polishing is to use Ceramic membranes. In most oilfields, due to a large concentration of oil remaining in the treated produced water, the only option left behind was hydraulic fracturing. Therefore, Ceramic membranes have been identified as a technology that has the promise of allowing produced water treatment without hydraulic fracturing. These membranes are capable of removing suspended solids above 0.05 microns in size and also remove dispersed oil to below 5 ppm [24]. One of the disadvantages associated with ceramic membrane is that there is continuous clogging of the membranes due to the fine oil droplets, and hence the cleaning of the membranes by steam blowing becomes very difficult.
4 SLUGGING

Slugging is a phenomenon that may occur in risers and pipelines carrying a two-phase fluid of liquid and gas. It is in general bursts of liquid pushed by pockets of gas. It causes large pressure variations and kinematic forces, because of varying flow-rates in the fluid. This can cause problems in the design and operation because of the kinematic forces, the pressure cycling, control instability, and inadequate phase separation. It also greatly affects the design of the receiving facilities [25]. The development of slug flow regime starts from stratified flow due to three main factors. The first is natural growth of small disturbances present in the flow, called hydrodynamic slugging. The second is accumulation of the fluid caused due to the slope changes in the profile of the duct, called terrain induced slugging. The third is related to instabilities due to start up and shutdown of the flow [26], which will not be examined further in this report.

Hydrodynamic slugging

Hydrodynamic slugging is a type of slugging that takes place in horizontal and nearly horizontal pipelines. It is a result of difference in the flow-rates in the multiphase flow, where gas flow-rate is faster than the liquid flow-rate [27], or due to the interfacial instability [28]. As the velocity difference between the gas phase and the liquid phase develops, waves start to form in the liquid phase. When the velocity difference becomes high enough, the waves on the liquid surface can cover the entire cross section of the pipe, which in turn blocks the gas flow creating a hydrodynamic slug. The slug is being pushed by the gas and so travels with a high velocity, sweeping in more liquid and causing turbulence within the slug [25, 381] [29]. Hydrodynamic slugging can be seen in figure 28.

Terrain induced slugging

The topography is the major cause for terrain induced slugging in pipelines with undulating terrain [30]. Liquid tends to accumulate at the lowest points of the pipeline as a result of gravitational effects. The gas is then trapped behind the liquid and pressure starts to build up. When the pressure is large enough, the liquid is forced out of the low spot and a slug is formed [26] [28]. These slugs are formed in the upwardly inclined section of the flow line and will steadily decay and finally collapse in horizontal or downwardly inclined sections, as seen in figure 29.
Severe slugging

Severe slugging in a pipeline is a special case of terrain induced slugging. Severe slugging occurs in pipelines with rugged terrain, having low liquid velocity, one downward inclined section, one riser, and a constant separator pressure. As seen in figure 30, it generally takes place in five stages. The riser base gets blocked by liquid, and gas is not allowed to flow through. The two-phase flow continues to enter the base and the pressure increases, increasing the water level. The gas-liquid interface is pushed up the riser, and the gas is gradually compressed. When the liquid reaches the top of the riser, the pressure is at its maximum and liquid will flow out of the riser. When the gas enters the riser it will start to expand, leading to faster liquid flow at the top. When the gas penetrates at the top of the riser, it will lead to a depressurization. The pressure is now at minimum, which leads to fallback of the remaining liquid, and the cycle repeats. Severe slugs may also come in shorter bursts, and in combination with hydrodynamic slugs [32].

Slugging problems

Slugging can cause many problems. Large and fluctuating rates of gas and liquids can induce severe mechanical vibrations in the pipe and severely reduce the production, and in the worst case shut down or damage the downstream equipment like compressors or separator vessels.

The large amount of liquid flow entering the separator might lead to separator overflow [30]. This may also cause high pressure build up in the separator, which may further damage the equipment. It also greatly affects the separation quality. The gravity separator relies on gravitational forces to separate the heavier water and particles from the oil, and should have close to steady state conditions to work optimally. Bursts of water, oil or gas will disturb this process, not allowing the phases to settle properly, leading to inadequate separation, and this makes controlling separators
Effect of corrosion is directly proportional to the slug frequency, although it is not correct at low slug frequencies. In catenary risers, inclination changes continuously from horizontal to vertical over large distances. Analysis of corrosion indicates that the severity of corrosion is proportional to the deviation angle because the corrosion is severe at the water hang up [33].

Controlling slugging topside

Severe slugging topside is controllable with subsea equipment, for instance it is possible to reduce the slugging by either manipulating the flow-rate of liquid going into the pipeline subsea, or by equalizing the pressure difference with valves when slugs appear. A smaller diameter of the flow-line will lead to a faster velocity in the fluid and reduce slugging, but will increase the flow-line pressure drop and reduce the capacity. An effective strategy to eliminate the probability of slugging is the automatic feedback control which has been discussed in Section 5.1.

Slugging can also be prevented by increasing the back pressure in the pipeline, by for example increasing the pressure in the separator. Also a technique called gas lift could be used to reduce slugging. Here the gas is compressed before being injected into the pipeline, although this is very expensive [34]. Subsea separation will increase production and reduce slugging, but not remove it completely. Slug catchers are also used extensively topside and on receiving facilities onshore, as seen in figure 31, where an onshore slug catcher of the inclined type is shown.

Controlling slugging subsea

Topside slugging can be controlled rather easily, but slugging occurring before the subsea separator is challenging to control. In many cases the slugging is uncontrollable and the equipment must be designed to deal with it. In other cases it is possible to deal with it, and a common way to do so is with a slug catcher. The main function of the slug catcher is to separate gas from liquid, and also to work as a temporary storage for the liquid. The slug catcher is installed upstream of the main processing equipment. An illustration of the slug catcher position is seen in figure 32.
The slug catcher should be designed to handle the largest slug that is expected to occur for that environment. It is basically made up of two parts: a gas-liquid separator under steady flow conditions, and a storage where the receiving liquid is accumulated. The slug catcher is generally made up of a pressure vessel, or a series of parallel inclined pipes in order to give the hold-up volume for the liquid. The inclined type discharges gas at the top pipes, and liquid at the bottom pipes. It needs to have a strong structure and foundation to withstand the impact of the slug. Due to its massive size, this slug catcher type is difficult to use subsea, but more compact versions exist, like the slug catcher in figure 33. This compact pipe slug catcher is a new technology, but is based on a mature technology used onshore. This slug catcher could also be integrated as a load bearing structural part in the subsea station, which will reduce the installation weight. The MultiPipe type looks like a feasible alternative as it gets many of the advantages from the inclined pipe type slug catcher, while remaining more compact and thereby easier to install. In figure 33, a MultiPipe slug catcher and an illustration of an inclined slug catcher is seen.

The pressure vessel type works more or less the same way as a gravity separator. A multi-phase flow enters the pressure vessel, and the gas is separated out of the liquid before it hits the downstream equipment. An illustration of a pressure vessel type can be seen in figure 34.

The pipe type can handle larger slugs and are more cost effective than the pressure vessel type, as well as having less operation problems. The pressure vessel type is, however, more compact...
and easier and cheaper to install, and that is why it could be useful for certain applications like subsea installations. It can also handle slugs at higher pressure than the inclined pipe type [31]. A third type also exists, which basically is a combination of the two others, where the gas and liquid are separated in a vessel, and the liquid is stored in large horizontal pipes [31].

Figure 34: Pressure vessel type slug catcher [36].

Slug catchers stabilize the process, work as an initial phase separation, and as a temporary storage of liquid. The flow into the separator will behave much closer to steady state flow because of the slug catcher [25].
5 MONITORING AND MEASUREMENTS

In a well-integrated subsea processing system, one of the most important issues is to deal with the produced water, either by re-injecting back to the reservoir or by simply discharging into the sea after separation. A highly reliable and real-time measurement and monitoring system is thus needed to ensure the water meets the requirements and not cause severe damage to the environment.

It is obvious that measurement is indispensable before the water is discharged into the sea. But as the water comes from the reservoir, there might be some doubts as to why measure is needed if we just re-inject the water back to where it comes from. This is because after separation, there are still some residual oil droplets and solid particles in the produced water, which may deposit in porous media if the produced water is re-injected to the reservoir directly. This deposition can cause severe damage to the formation with a significant reduction in permeability. And any decrease in permeability would decrease the injectivity index and consequently the production, both oil production rate and the total amount of oil that can be ultimately recovered from an oil field, which is obviously not favorable at all. Therefore it is very important to measure the amount of oil droplets and solid particles to ensure the quality of the water meet the requirements.

Composition of produced water

The properties of the produced water mainly depend on the location, type of formation and type of hydrocarbons of the field which always differ from one to another. Since the produced water mainly comes from the geological formations, which develops in millions of years, its composition is highly field-dependent.

Produced water contains majorly water, and minor amounts of organic and inorganic constituents from the source geologic formation and the associated hydrocarbons. This might change during the lifetime of the reservoir due to the water injected to maintain the pressure. Besides, it may also consist of small amounts of chemicals such as Hydrate Inhibitors, Dehydrators, and Scale Inhibitors etc. which are injected for the treatment of water.

Regulations and standards

Since it is impossible to remove all the oil and chemicals out of the water, here comes another question: to what extent should we deal with this water in consideration of cost and environment at the same time? The general way is to refer to some standards, which are shown in table 2.

Besides, there is also a great concern about the toxicity of the water since there could be a lot of chemicals which are poisonous to sea creatures. In the US, people use shrimps to test the quality of water [37].

Measurement method in existing equipments

At present, there are only three liquid-liquid separation systems installed subsea, two in the North Sea, operated by Statoil and one outside Brazil, operated by Petrobras. All of them have a system for water injection from the seabed included. For either Troll Pilot or Tordis SSBI, there have been no on-line continuous water quality measurement devices installed. The water...
Table 2: Regulation and standard [37]

<table>
<thead>
<tr>
<th>Area</th>
<th>Standard</th>
<th>Effluent Permit Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mediterranean</td>
<td>Barcelona Convention</td>
<td>40 mg/L monthly average</td>
</tr>
<tr>
<td>Red Sea</td>
<td>Kuwait Convention</td>
<td>100 mg/L per day max</td>
</tr>
<tr>
<td>North Sea</td>
<td>OSPARCOM</td>
<td>30mg/L oil in PW</td>
</tr>
<tr>
<td>Gulf of Mexico</td>
<td>US Regulations</td>
<td>29 mg/L monthly average</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40 mg/L daily max</td>
</tr>
<tr>
<td>Baltic Sea</td>
<td>Baltic Sea Convention &amp; Helcom</td>
<td>15 mg/L monthly average</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40 mg/L per day max</td>
</tr>
</tbody>
</table>

...quality checks were carried out using ROV’s extracting samples. The samples were then taken to the surface for analysis. This method can not provide real-time, continuous information of the quality, so it is still impossible to discharge directly to the sea at the moment.

- **Troll – Statoil, North Sea**

The produced water is injected in a low-pressure aquifer, thus it is not used for pressure support on the Troll field. Besides, the Troll Pilot is designed for negligible sand production, so the system is not working continuously.

The water quality was measured from ROV and the samples taken from sampling points subsea were brought back to the surface. The results from the last sample taken when the processing station was producing at 100 % design liquid flow rate, was 15 ppm oil in the water, which is cleaner than the requirement for discharge directly to sea of 40 ppm [38].

- **Tordis – Statoil, North Sea**

Water injection is used for pressure support and the water injection pump can be retrieved for maintenance by a pump-running tool, so this system is neither working continuously.

When Tordis SSBI was installed, the original plan was to inject the separated water together with sand into the reservoir downstream of the water injection pump. But due to fracturing of the formation in 2008, this injection well is no longer used. Water and sand are now transported to the surface in a separate pipe and processed on the Gullfaks C platform.

- **Marlim – Petrobras, Brazil**

There is no proper geological formation near Marlim field to take the produced water, so it was decided to re-inject the separated water back to the reservoir itself.

Between September 2006 and October 2009, a PWRI (Produced Water Re-injection) trial aiming to test the injection in core samples and filterability in membranes was carried out in P35 (one of the FPSOs located on the center of the field). During the trial, water quality was not well monitored, but it is known that the process plant was not operating adequately. The basket filters with 80 µm openings and with 500 µm openings were tried separately [39].

The problem is that after some operating time, the filter needs to be cleaned due to clogging, which is impractical in the real operation. Another challenging problem is that the filtration
properties might change as time goes on, thus the opening diameter needs to be changed. For instance, in 2005, 0.45 µm membranes seemed to have good filtration properties, but one or two years later, even the 80 µm basket filter was clogged pretty fast, and this also happened to the plate type heat exchangers [39].

**Methods**

Although for the existing subsea separators, no measurement method is under use except the ROV (and they already stop doing this), some methods have been used topside and a lot of works have been done to explore the feasibility of different methods and promising results are shown. In addition to the environmental aspects, cost is another reason why measurement is demanding. For instance, a measurement error of just 0.1 % water content in the multiphase flow will lead to a loss of $25 000 (according to Gimson, 1989). In this chapter, several different methods that might be used in subsea separation are introduced.

**Tomography method**

Tomography is a non-invasive technique used to get visualized information over a cross-sectional segment of a vessel or pipeline. This kind of method has been used in many different places for monitoring the properties of heterogeneous mixtures. The data can be collected based on several different measurement techniques, such as the optical, electrical, microwave, ultrasonic, radioactive and so on. Since for oil and gas production applications, the electrical tomography is fast, sensitive and meanwhile structurally robust, this paper will only focus on this method.

In the electrical tomography method, the data are collected from the sensors installed on the periphery of the vessel or pipelines to reconstruct the dielectric properties. Under this measurement method, there are mainly two types which are discussed below.

**Electrical resistivity tomography (ERT)**

ERT utilizes the differences of conductivity or resistivity in the detection zone and can be used for observing the distribution of oil and air in water inside a deoiling hydro cyclone. This will give some information about the performance and operational variables such as oil concentration, droplet size and so on.

An illustration of an ERT transmitter with 12 probes is shown in figure 35 and one ERT sensor configuration is shown in figure 36. At each sample, one of the probes is set to be active while the rest are passive. The active probe launches a 5 voltage signal to the system and the voltage drops from the active probe to all the rest passive probes are measured. And then at the next sample, another probe is set to be active while the rest is passive. All the probes will be active once after 12 samples and thus a complete grid mapping resistance over the cross-section will be achieved [40].

Many researchers did a lot work to explore the possibility of applying this method to hydro cyclones. M.A. Bennett et al.(2004) conducted an experiment using a 70 mm diameter deoiling hydro cyclone and found that a relatively stable flow is needed to get a clear picture. This requires faster flow rate in the cyclone [41]. Durdevic et al.(2015) constructed a pilot plant made up with a 50 mm pipe, and found that for a relatively stable water/oil interface, the generated
2-D tomograms can clearly show the picture of it, while for dynamic flow, only the gas/water interface can be determined [40].

The experiments conducted all show some valuable results and thus prove that this method is a suitable one for the separation, especially the cyclone separator. However, some difficulties still exist for the laboratory scaled experiments. Therefore, further work on testing the oil/water concentration to simplifying the use of imaging for control purpose should be investigated.

**Electrical capacitance tomography (ECT)**

Figure 37 shows the schematics of an electrical capacitance tomography (ECT) system equipped with 8 electrodes. The measurement protocol can be considered as that the electrical field rotates in discrete steps around the pipe cross-section. In the medical imaging, the computerized tomography also uses a similar source-detector movement.

A capacitance-based tomography system developed by Isaksen et al. (1994) are shown in Figure 38 for interface imaging inside a separator. The test for real-time imaging of water, oil and gas interface levels was conducted in a laboratory separator with internal diameter of 1 meter. The accuracy was good enough, less than 1.0 cm for all phases [42].

The capacitance-based model is good enough for the simple processes while for a more complex one, this method is not sufficient to get the reliable information. Thus, a dual-modality system is needed and recent years, many researchers have done a lot work on this field. For example, Johansen et al. (1996) proposed a multi-modal system with the combination of electrical capacitance and gamma-ray for multiphase hydrocarbon flow, which could also be used for the monitoring
of primary separators. Hjertaker et al. (2005) improved this kind of system to make it possible to monitor the full water-cut range of the process water [42].

**X-Ray scatter method**

This is the technique for measuring the concentrations of oil and water in emulsions extracted from oil fields using energy-dispersive X-Ray scatter (EDXS). It is very important for the oil industry to measure oil to water ratio of the fluids extracted from oil fields. Therefore a low cost system was developed using the energy dependence of coherent scatter to measure oil water ratios. EDXS is the measurement of low angle scattering of photons from a polychromatic incident beam. The ratio of oil to water is calculated by measuring the relative scattering of emulsion at two energies. This technique to measure water content in the oil water emulsions has great application in multiphase measurement. This measurement technique has been shown
to be independent of the flow rate of gas and hence suitable for online multiphase monitoring for a range of flow rates.

**Single-electrode capacitance probes**

One of the usual measurement devices is the probe device. The probe device is a rod looking device which is placed inside the vessel (intrusive). The thermography is for instance extrusive, not penetrating the separator. The single-electrode capacitance probes is based on measuring the capacitance in different flowing medium. The dielectric constant for each medium is different. The resulting capacitance that is measured is then based on the phase configuration. The disadvantage of this method is that it can not distinguish between phases with similar value of measured capacitance. This means that the interfaces which are uneven because of, for instance foam, can make the oil water contact harder to measure. So to use the method, some assumptions are needed: The fluid height needs to be constant and a clean oil-water interface is needed. [43]

![Figure 39: Example of a single-electrode capacitance probe.](image)

**Wave reflections**

This method is based on the wave reflection phenomena which is occurring at the interface between phases. As with a single electrode capacitance probe, this method does not work well for phases in a mixed state and uneven interface (foam etc). The method is either based on ultrasound or microwaves. If the ultrasound method is applied, an ultrasonic gauge is installed at the bottom of the separator. The device is transmitting and receiving ultrasonic pulses along a vertical axis. When the wave is hitting an interface, it gets reflected and goes back to the device. This can indicate the water-oil level and indicate variation in the level of liquids in the separator. The limitation in this method besides the ones already mentioned, is multiple reflections from the walls, and the measurement is also sensitive to temperature changes. This requires careful analyzing and interpretation of the data [43].
If the microwave technique is used, a microwave generator and a detecting diode is used to determine the microwave reflection coefficient at various positions through the tank. A method developed in 2008 used a level detection probe where the microwave is guided along a "rope" and is reflected by the interface of different dielectric constants. The probe registers the signals and a microcomputer identifies the level of the echoes. The echoes which consists of different amplitudes and phases is converted into level information. Advantages with this method is that it is not depended on density, unlike ultrasound. This could be an advantage if there is a phase change for instance [43].

**Magnetostrictive level gauge**

A sensing rod is mounted along the motion axis to be measured. The sensing rod consist of a position ring (a magnet) which travels along the sensing rod. This magnet has a density so it remains between the interface of oil and water. Inside the rod, a wire made of magnetostrictive material is placed (waveguide), and through this wire a current impulse is sent which generates a circular magnetic field around the waveguide. If this magnetic field comes in contact with the
magnetic field from the magnet ring which is free to slide, a density wave is triggered where the two magnetic fields are in contact. This new wave will propagate in the waveguide towards a sensor head. The distance between the magnetic ring and the sensor head can then be calculated. This can be used to measure multi-interphases, for instance gas-foam, foam-oil, water-solids etc. By inserting several probes, emulsions could also be detected [43] [44] [45].

![Schematic example of how a magnetostrictive level gauge works](image)

Figure 42: Schematic example of how a magnetostrictive level gauge works

Other promising methods

In addition to the methods mentioned above, there are also many other potential technologies that have already been developed for several years, including erosion, microscopy image analysis, Laser-Induced Fluorescence (LIF), light scattering, so on and so forth. Erosion and acoustic based technologies are now used to provide useful information for sand detection and monitoring, but for produced water applications, they are not sensitive enough. For the measurement of produced water quality, image analysis, ultrasonic and a combination of LIF and image analysis based systems are very promising in today’s market. But they are all relatively new technologies to the oil and gas industry and still facing a lot of problems especially fouling of the optical windows [46].

In our view, the Tomography methods especially the Electrical Resistivity Tomography methods might be the best choice for subsea separator. First of all, the tomography method is non-invasive and thus will not reduce the robustness of the separator. In addition, ERT has been used for clay refining solid-solid hydrocyclones previously and proved to be suitable for water-oil cyclone separator. Although further development is still needed to put this method into commercial use, it seems to be the most promising one for subsea separation.

Calibration

After the collection of data, a calibration is needed to test whether the value is correct or not, whether they are trustable. This is extremely difficult for the real-time oil in produced water monitoring. This is because the great variation of the produced water stream and also it’s hard to simulate the water in a laboratory environment.
In our view, two kind of solutions are practicable for this issue: the first one is that we can have two measurement instruments to compare the value with each other. When the values from the two instruments are almost the same, we consider this to be correct since it is almost impossible to have the same wrong value at the same time. The other one is that we can set the ROV periodically to take some samples and analyze in the surface lab to check whether the instrument is working properly.
5.1 CONTROL AND INSTRUMENTATION

The instrumentation refers to the hardware part of the control system like measuring instruments, transmitters, valves etc. The operation of the separator is a continuous process which has the constant inlet flow, and the gas and the liquid has to be removed continuously. In case of liquids, the monitoring is done by means of level controller as seen in figure 43. The level controller senses whether the liquid level is high or low, and adjusts its valve accordingly to maintain the liquid level in the separator and a constant flow at the outlet.

From figure 43, as more gas enters the separator, there will be a rise in the pressure in the separator. Therefore there is a need for pressure controller at the top of the separator or at the outlet gas piping to monitor the pressure. The opening of the pressure control increases when the pressure is higher than the set-point and closes when the pressure is below the set-point, thereby maintaining the pressure in the separator at the desired value.

LLCC: From figure 44, we observe that there are pressure transmitters at the inlet of the LLCC, at the oil rich outlet, at the water rich outlet, and also a coriolis meter to measure the flow rate at the water rich layer.
**Anti-Slug Control:** As mentioned in Section 4, severe slugging usually takes place in pipelines carrying multiphase mixture from the seabed to the surface. As shown in figure 45, at a given pressure set point, the topside choke valve is used to control the riser base pressure. It can be seen that the topside choke valve is the manipulated variable and the pressure at the riser is the controlled variable [47].

![Figure 45: Topside choke "anti-slug control" [47].](image)

**Design Safety:** There is a need for safety system to prevent overpressure, equipment rupture, pollution, fire and personnel injury. Two layers of protection exist in a safety system, namely primary and secondary protection.

Primary protection is a sensor on the equipment that detects the undesirable occurrence. For example, the equipment usually had the level, pressure or temperature sensor to detect values that are too high or low in comparison to the set-point. When the primary protection fails to operate, there is a secondary protection system consisting of Pressure Safety Valve (PSV). This safety valve relieves the excess pressure in the vessel which is resulted by the over-pressurization and vents to the flare. A separator with a given operating pressure will have a design pressure which is termed as Maximum Allowable Working Pressure (MAWP) to prevent over-pressurization due to small fluctuations in the process conditions.
5.2 MODELING

Models

Modeling is used in nearly all parts of science and engineering, and is the basis for design and operations. It is used from the design of specific parts of equipment, to design and optimization of the parameters for a whole system. For operations, models are used for control design purposes from a basic-level, to an intermediate-level where more advanced technologies for model-control is used, up to a high-level model for controlling and coordinating the actions for a whole plant. Models are also used on a top level for production planning and logistics. For chemical engineering, the modeling, in terms of operations, is often split into three parts: low-level models for basic controllers, medium-level models for model-predictive controllers, and high-level models for control-optimization [48].

What is a model?

Models are used to mimic the physical behavior, and to map behaviors into objects. Therefore they are very important for any kind of work where the objective is to exploit the objects behavior. To base the model on a mathematical formulation provides answers and guidance useful for the originating application, and it enables a better understanding of the system being modeled. Hence, from now on the model will refer to a mathematical model. We can define the mathematical model taking place in three major steps [48]:

- **Primary mapping**: The first major step is to convert the plant into models based on mechanistic equations derived from physics, fluid mechanics, thermodynamics, etc. The results of this operation are either a set of ODE’s, algebraic equations (AE’s), or a set of PDE’s.

- **Model simplification**: Here we take into account the order-of-magnitude assumptions which leads to the simplification of the model. Additionally mathematical simplification may be introduced, such as polynomial approximation to simplify the model.

- **Model fitting**: Adjusts the model to the plant by minimizing prediction-result mismatch.

Based on these principles the model can be constructed in two different ways. The first is a mechanistic model, often referred to as **White Box Models** or **First Principles Models**, which is derived purely from physics. The second is referred to as **Black Box Models**, and the reason for using this more often, is due to the unavailability of the process mechanics, or it is too complicated for the intended application. Another reason to use it is because of lower computational complexity and reduced computation time. Both the "boxes" do not exist purely, therefore a combination of the two approaches is used, which is termed as **Grey Box Modeling**. Simulation of process models is very important for the design, safety analysis and controller synthesis of the process. Therefore there is a necessity of prior trial of the controller on a process model before the implementation of the plant.
Models for the separator

A separator is controlled using the outlet flow rates of gas and water. The water outlet quality and oil outlet quality are variables of significant interest, though they are not always measured. Modeling helps to estimate the variables of interest based on available measurements. Tamal Das, a PhD candidate from NTNU, is carrying out research on developing control oriented process models for separators such as gravity separators, cyclonic separators for subsea oil and gas processing. One way of doing this is by designing state observers, Leunberger observers, to estimate the unmeasured states like the quality using the known measurements such as pressure and level.
6 CONCLUSION

There are currently three installed subsea separation systems worldwide. As previously mentioned, subsea separation has its pros and cons compared to topside. Table 3 summarizes the advantages and disadvantages of subsea separators.

Table 3: Advantages and Disadvantages of subsea separation

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dispose or reinject water without wasting energy on pumping it up to the platform</td>
<td>May have higher investment cost</td>
</tr>
<tr>
<td>Increase platform integrity, do not need big separators installed topside</td>
<td>Installation vessel capacity is a limiting factor during installation</td>
</tr>
<tr>
<td>Reduce the pressure drop, especially helpful at deep waters</td>
<td>The subsea structures are not easily accessible which makes maintenance, control and monitoring a challenge.</td>
</tr>
<tr>
<td>Allows to create several satellite wells connected to one FPSO or platform</td>
<td>Climatic condition is a deciding factor that may affect and delay the installation.</td>
</tr>
</tbody>
</table>

Three separation devices have been reviewed and none seem to be clearly superior over the other as all had their own advantages and disadvantages. The optimal separation system would therefore be one that selects the separation device or combines them to fit a/the given well(s) best.

Table 4: Advantages and disadvantages of different subsea separators

<table>
<thead>
<tr>
<th>Separator type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity Separator</td>
<td>1. Simple principle</td>
<td>1. Large size</td>
</tr>
<tr>
<td></td>
<td>2. Reliable</td>
<td>2. Difficult to install</td>
</tr>
<tr>
<td></td>
<td>3. Efficient</td>
<td>3. Expensive</td>
</tr>
<tr>
<td>Cyclone Separator</td>
<td>1. Smaller size</td>
<td>1. Not tested</td>
</tr>
<tr>
<td></td>
<td>2. More suitable for high depth</td>
<td>2. Limited knowledge</td>
</tr>
<tr>
<td>Swirl Separator</td>
<td>1. Compact</td>
<td>1. Not efficient to separate high oil cuts in water</td>
</tr>
<tr>
<td></td>
<td>2. Easy to install</td>
<td>2. Not tested</td>
</tr>
</tbody>
</table>

Slug catchers

The most effective way to handle slugs, subsea is to install a slug catcher. The two types mentioned in detail is the pressure vessel type and the inclined pipe type. A summary of the advantages and disadvantages are found in table 5.

The MultiPipe type of slug catcher is a promising slug catcher type, with the advantages of the inclined pipe type, while keeping it more compact and thereby easier to implement subsea. In the end, the needs of the field should be the deciding factor with respect to the type of slug catcher to be installed.
Table 5: Advantages and disadvantages on two different slug catcher types

<table>
<thead>
<tr>
<th>Slug catcher Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure vessel</td>
<td>1. Compact</td>
<td>1. Less cost effective</td>
</tr>
<tr>
<td></td>
<td>2. Easier and cheaper to install</td>
<td>2. Can not handle larger slugs</td>
</tr>
<tr>
<td>Inclined pipe</td>
<td>1. More cost effective</td>
<td>1. Large size</td>
</tr>
<tr>
<td></td>
<td>2. Can handle larger slugs</td>
<td>2. More difficult to install</td>
</tr>
</tbody>
</table>

In addition, for a well-integrated subsea processing system, a highly reliable and real-time monitoring and measurement system is needed to ensure the produced water meets the requirements and not cause damage to both the environment and the formation. Although for the existing subsea separators, no measurement method is in use, except the ROV (and they already stop doing this), a lot of work have been done to explore the feasibility of different methods and promising results are shown. A summary of the advantages and disadvantages for some potential methods is shown in table 6.

**Measurement methods**

Table 6: Potential subsea measurement methods [40],[42],[43],[44],[45],[49].

<table>
<thead>
<tr>
<th>Methods</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Tomography Method</td>
<td>1. Non-invasive</td>
<td>1. Only test in Lab for</td>
</tr>
<tr>
<td></td>
<td>2. Can be used for cyclones</td>
<td>oil-water separation</td>
</tr>
<tr>
<td></td>
<td>3. Experience in solid-solid hydrocyclone</td>
<td>2. Moderate spatial resolution of the resultant image</td>
</tr>
<tr>
<td>Ultrasound</td>
<td>1. Well-tested</td>
<td>1. Echo from the walls affect measurements</td>
</tr>
<tr>
<td></td>
<td>2. Easy to use</td>
<td>2. Sensitive to temperature change</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Careful calibration data required</td>
</tr>
<tr>
<td>Microwave</td>
<td>1. Independent of density</td>
<td>1. Need a relatively stable interface</td>
</tr>
<tr>
<td></td>
<td>2. Easy to use</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. High accuracy</td>
<td></td>
</tr>
<tr>
<td>Single-Electrode Capacitance</td>
<td>1. Low cost</td>
<td>1. Reduced robustness of separator</td>
</tr>
<tr>
<td>Probe</td>
<td>2. Easy principle</td>
<td>2. Need a relatively stable interface</td>
</tr>
<tr>
<td></td>
<td>3. Experience in offshore</td>
<td>3. Cannot distinguish different phase configurations with same capacitance</td>
</tr>
<tr>
<td>Magnetostrictive Level</td>
<td>1. High accuracy</td>
<td>1. Need a relatively stable interface</td>
</tr>
<tr>
<td></td>
<td>2. Can measure multi-interfaces</td>
<td>2. Easy to be affected by the deposition in Crude oil</td>
</tr>
<tr>
<td></td>
<td>3. Potential to identify the presence of emulsions</td>
<td>3. Moving parts</td>
</tr>
<tr>
<td></td>
<td>4. Can obtain phase profiles</td>
<td>4. Dead band on both sides of sensor</td>
</tr>
</tbody>
</table>
The future

Currently the oil recovery factor is around 60% for offshore platforms and 50% for subsea installations [50]. We have discussed a lot of advantages with subsea separation and subsea in general, and even though the current recovery factor is usually bigger for platforms, the goal is to change this in the future. Subsea separation is very expensive and a lot of people still wonder why the separators and other components should be installed at the seabed despite the advantages discussed in this paper. Subsea separation is still in an experimental phase, and new innovative methods is needed to make new steps in the oil industry to get increased oil recovery and reduced costs, which is crucial at this stage (low oil price, high costs etc). Subsea separation is one of those new innovative methods and has shown promising results. This is still in an early stage of the experimental phase and with new technology and time, a lot of improvements will appear. Based on the positive progress which have been done, subsea separation and subsea in general will be the future. When Statoil was planning on building a subsea gas compression device, engineers thought they had lost their minds and meant it was impossible. Some years later when it was installed and started to operate successfully in 2005, engineers and oil companies where envious and had to bury their words. This compression device increased the oil recovery a lot, and there were still room for a lot of improvements. This shows that there is a bright future for subsea, and subsea separation will with time be cheaper and more efficient. This expensive experimental phase is necessary, since the easy oil has been recovered, and the more difficult oil remains, which requires more complex technology in the future.
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