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Abstract

The production of petroleum resources includes co-producing water. This water contains oil products and needs to be treated before discharge to sea or re-injection into the reservoir. The amount of produced water increases with the age of a field, as does often the amount of solids. The pressure of the reservoirs will decrease with time.

The primary equipment for treating produced water is the hydro cyclone. It's operated with a lower limit with regards to oil droplet size of ~10 µm although smaller oil droplets have been experienced to separate. The hydro cyclone requires a certain differential pressure to perform at its maximum efficiency, and it is sensitive to solids. To protect the hydro cyclone a desanding cyclone could be installed upstream the hydro cyclone. A pump is often used to pressurize the water if necessary. The effect that this equipment has on the oil-water separation is a topic being discussed in the industry.

The development in the industry, with increasing the life lengths of the fields and the need for development in areas of more stringent requirements, will benefit more knowledge regarding the effect of pumps and desanding cyclones on the oil- water separation.

This thesis deals with these issues and presents the knowledge that exists with regards to pumps and desanding cyclones and their effect on oil droplet coalescence and break-up. This research has been done through contacts with suppliers, literature studies and evaluation of available test data related to this equipment.

The literature survey and contacts with pump suppliers reveal that little work has been done to identify any effect of the pumps on the oil droplets. Both the literature survey and the suppliers agree that the eccentric screw pump generates the least droplet break-up, and that the centrifugal pump creates more shearing than other pump types.

The offshore tests of centrifugal pumps and twin screw pumps indicate that the twin screw pump is gentler to the oil droplets than the centrifugal pump. While the tests of the centrifugal pumps indicate that increasing differential pressure increases droplet break-up, the twin screw pumps do not show such correlation. This indicates that the twin screw pump is more suitable, with regards to oil droplet sizes, for boosting the produced water to a hydro cyclone.

The literature survey and the contacts with the desanding cyclone suppliers reveal that little work has been done to identify any effect of the desanding cyclone on the oil droplets. The experience of the suppliers is that the desanding cyclone gives coalescence, while the one revealed test show that the desanding cyclone isn’t damaging to the downstream separation.

The offshore tests indicate that the desanding cyclone create coalescence or an insignificantly degree of break up and will not damage the oil removal performance of the downstream equipment.

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Preface

This master thesis was written in the last semester of my study within Offshore technology, Environmental Engineering at the University of Stavanger.

The thesis was carried out at StatoilHydro Technology and New Energy, department of Process and Refining Technology with the Process Technology area. Thank you for making room for me in the department and allowing me to perform my work at your office at Forus Øst, Stavanger. I have really enjoyed working with this thesis and being a part of the good working environment at StatoilHydro.

I especially want to thank my supervisors, Cecilie Fenne Willumsen at StatoilHydro and Tor Heitmann at Mator. Thank you for taking the time to guide me through this thesis and for sharing your knowledge with me. I also want to thank my instructor at the University of Stavanger, Torleiv Bilstad. Thank you for supporting me in the writing process.

Finally I want to express my gratitude to everyone who has helped me acquire the information and data I needed to carry through this thesis. I couldn’t have done this without your time and effort.

1 Introduction

Producing petroleum resources involves co- producing amounts of water which is called produced water. The produced water will contain variable amounts of dispersed and dissolved oil, chemical residues, and solids. To discharge produced water to sea or re-inject it into the reservoir, it is necessary to treat it to remove components that are harmful to the environment or that might interfere with the injection process. The environmental requirement for produced water discharge today is 30 ppm dispersed oil.

The most common process system, where the oil, gas and water are separated, has 3 separation steps. The water from these separation steps is routed to a produced water treatment system. The primary equipment for treating produced water is the hydro cyclone, potentially with a degassing tank downstream. It’s recognized that the hydro cyclone has a lower size limit for removing oil droplets, and it’s usually operated with 10 µm although smaller droplets have been experienced to separate.

As stated the produced water commonly contains solids, and as the fields age they will often produce increasing amounts of solids. A desanding cyclone could be installed upstream the hydro cyclone to remove the solids from the flow and protect the downstream equipment.

There are different views on how the desanding cyclone affects the oil droplets.

Some believe that the shear forces in the desanding cyclone will break up the droplets and be damaging to the downstream separation process. Others believe it can make the droplets coalesce and be beneficial to the separation.

Some fields have low pressure reservoirs from early production, while others are pressure depleted over time. This influences the produced water treatment system by introducing low pressure water from the separators. The last step of the separator train almost always operates at low pressure. The hydro cyclones require a certain differential pressure to perform at its best efficiency. To achieve this in low pressure systems a pump is often installed boosting the pressure upstream the hydro cyclone. Pumps are generally viewed as damaging to oil droplets, and suppliers often talk about different pumps as low or high shear referring to the pumps ability to avoid breaking up oil droplets.

The problems as presented above are becoming increasingly important for several reasons:

- Many of the fields being operated today are relatively old fields.
- The life length of the fields is increased by using improved recovery techniques.
- Environmental requirements are stricter in new areas, like the arctic.

This development introduces an increasing need for installing desanding cyclones and pumps into the produced water systems without reducing the oil removal efficiency of the hydro cyclone. This requires knowledge about how these equipments affect the oil droplets.

The purpose of this thesis is to acquire the knowledge available relating to the effect of the pumps and the desanding cyclone on oil droplets.

Methods used to achieve this are:

- Contact with suppliers of the equipments and produced water packages
- Contact with other relevant companies
- Literature surveys
- Evaluation of available test data on droplet break-up and coalescence
- Have new measurements performed at relevant fields and evaluate the test data

2 List of figures

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4 Produced water treatment

Treating the produced water is a challenging task with stringent requirements to the oil content of the produced water.

Norway has committed itself to the OSPAR (Oslo-Paris) Convention, the convention for the Protection of the Marine Environment of the North-East Atlantic that applies to offshore industrial activities. The OSPAR Recommendation 2001/1 for the Management of Produced Water from Offshore Installations states that: No individual installation is to exceed a standard limit of 30 mg/l dispersed oil in produced water that is discharged to sea. After this achievement the contracting parties should continue to review the best available techniques (BAT) and the best environmental practice (BEP) regarding oil concentration (OSPAR Commission). Appendix A gives an overview of BAT as given by OSPAR (Vik 2009).

4.1 Principles behind PW treatment

The principles applicable in the process of oil-water separation and treatment of produced water are reviewed in this chapter.

4.1.1 Stokes law

The oil-water separation and the well stream separation are based on gravity separation, the separation of different fluids in the gravity field driven by the density differences between the fluids. Stokes' law applies to the sedimentation or flotation of non-flocculating, discrete and spherical particles, and is here modified to the application of oil droplets in produced water. Stokes' law, giving the terminal settling velocity of an oil droplet as shown in Equation 4-1, presumes laminar flow, spherical particles and unhindered settling.

$$V_t = \frac{g \times D^2 \times (\rho_w - \rho_o)}{18 \times \mu} \qquad \left[\frac{m}{s}\right]$$

Equation 4-1: The terminal settling velocity of an oil droplet, given by Stokes' law.

V_t = Terminal settling velocity of a droplet (m/s)

g = Acceleration due to gravity (m/s^2)

D = Droplet diameter (m)

ρ_w = Density of the water phase (continuous) (kg/m^3)

ρ_o = Density of the oil phase (dispersed) (kg/m^3)

μ = Dynamic viscosity of the continuous phase (kg/ (ms))

Stokes' law shows that the settling velocity increases by either increasing the droplet diameter (D), increasing the density difference between the phases ($\rho_w - \rho_o$), decreasing the viscosity (μ) of the continuous phase, or increasing the acceleration (g). It's still the droplet diameter that will affect the settling velocity the most (Husveg 2007).

If a hydro cyclone or other separation equipment based on centrifugal forces is used to separate the oil from the produced water, a slightly modified Stokes' law must be applied. For a particle that is forced to move in a circular path the gravity acting on that particle is proportional to the square of the angular velocity, as shown in Equation 4-2.

$$g = \omega^2 \times r \qquad \left[\frac{m}{s^2}\right]$$

Equation 4-2: The gravity acting on a particle forced to move in a circular path.

g = Acceleration due to gravity (m/s^2)

r = radius of the circular path (m)

ω = the angular velocity (m/s)

Inserting Equation 4-2 into Stokes' law as given by Equation 4-1, gives the terminal settling velocity for an oil droplet affected by a centrifugal force. This is shown in Equation 4-3. For explanations to the terms, it's referred to the explanations to Equations 4-1 and 4-2.

$$V_t = \frac{\omega^2 \times r \times D^2 \times (\rho_w - \rho_o)}{18 \times \mu} \qquad \left[\frac{m}{s}\right]$$

Equation 4-3: The terminal settling velocity of an oil droplet affected by a centrifugal force.

The droplet diameter is a great influence factor also in centrifugal separation, but the angular velocity is of equal influence to the terminal velocity. Equation 4-3 shows that there is a large potential for increasing the terminal settling velocity of the oil droplet, and this is used in all types of centrifugal separation (Grov 2007).

4.1.2 Dispersion

Droplet break-up (dispersion) and coalescence are the two major phenomena accepted in phase separation. Dispersion is the process where one phase in an immiscible system forms an unstable, heterogeneous state of two or more distinct phases dispersed in a continuous phase (Andresen 1999). This occurs when a large amount of energy is put into the system in a short period of time.

One large droplet will have a smaller surface energy than the two small droplets formed from it combined. All systems will always strive to have as low energy as possible. Therefore, an oscillating oil droplet will become unstable first when the kinetic energy equals the difference in surface energy between the large droplet and the potential two or more small droplets.

Hence, for the dispersion to occur the energy input must overcome the natural tendency of two immiscible fluids to minimize the contacting surface area between them.

Simultaneously as the dispersion, the motion of the oil droplets in the system will cause the smaller droplets to coalesce. Hinze has proposed a relationship for the maximum droplet size that can exist at equilibrium with regards to the coalescence rate and dispersion rate, shown in Equation 4-4:

$$d_{max} = 432 \times \left(\frac{t_r}{\Delta P}\right)^{2/5} \times \left(\frac{\sigma}{\rho_w}\right)^{3/5} \qquad [m]$$

Equation 4-4: The maximum droplet size that can exist at equilibrium with regards to the coalescence and dispersion rates.

d_{max} = droplet diameter where 95 % of oil volume exists in droplets smaller than this
t_r = retention time [minutes]
ΔP = pressure drop [psi]
σ = surface tension [dynes/cm]
ρ_w = density of the water [g/cm^3]

Equation 4-4 shows that the greater the pressure drop and thereby also the shear forces that a fluid experiences in a certain period of time, the smaller the maximum oil droplet diameter will be. Practically this shows that large pressure drops over small distances as in chokes, control valves, desanders and other shear components result in smaller drops. A conservative consideration of the dispersion process is that whenever large pressure drops occur, all droplets larger than d_{max} will disperse straight away (Arnold and Stewart 1998).

4.1.3 Coalescence

Coalescence is the reverse process of droplet break-up, with the system returning to the state of lowest total energy, i.e. separate homogeneous phases with a minimized common interface (Andresen 1999).

The process of coalescence in a water treatment system is more time- dependent than the process of dispersion. If two droplets in a dispersion of two immiscible liquids collide, it rarely ends with them coalescing. If the two colliding droplets are exposed to turbulent pressure fluctuations, and the kinetic energy of the oscillations induced in the droplet pair is larger than the energy of adhesion between them, the contact will be broken before coalescence is completed.

Droplets can coalesce due to binary or interfacial coalescence. Binary coalescence is when two droplets that are settling/ creaming or are packed in the dispersion band coalesce. Interfacial coalescence is coalescence of a droplet with its own phase (a droplet of infinite dimensions).

Either way a liquid film of the continuous phase separates the dispersed droplets and has to be drained and broken for the coalescence process to be complete (Andresen 1999).

The film has to be drained to a critical thickness (where it ruptures) before the coalescence can occur, and the time it takes for this thickness to be reached is called the critical drainage time. If the contact time between the droplets exceeds this critical drainage time coalescence occurs (Leng and Calabrese 2004).

The drainage of the film can be hindered by interfacial components. Three types of stabilizing mechanisms exists; (1) steric stabilization (surfactants), (2) electrostatic stabilization (charged components with overlapping electric double-layers) and (3) mechanical stabilization (particles attaching to the droplet surface), where as some authors view mechanical stabilization as a part of steric stabilization (Andresen 1999).

The time dependence of the coalescence process is one reason why Equation 4-4 can't be applied to predict coalescence in piping with high pressure drops downstream of a process component causing dispersion. In addition a basis to estimate the necessary time to grow d_{max} doesn't exist (Arnold and Stewart 2008).

As discussed in Chapter 4.1.2 dispersion will occur if the energy input to the system is too high. But if the energy input to the system is too low there will be very frequent droplet collisions giving little degree of coalescence. The coalescence rate is also affected by the concentration of the dispersed phase, with collisions happening more frequent with higher concentration. The coalescence efficiency is also reduced by decreasing droplet size (Arnold and Stewart 2008).

4.1.4 Fluid regimes and boundary layers

A fluid flowing through a pipe doesn't have even velocity throughout the pipe, and the variation is often visualized by using streamlines. The distance between the streamlines indicates the velocity; the higher velocity, the smaller distance between the lines. But the streamlines only show the net effect of the motion, and not the actual movement of the molecules. At slow fluid flow the image of the streamlines are quite correct, but with faster fluid flow there will be frequent movement of particles across these streamlines. This fast fluid motion is called turbulent flow, while the slow flow is called laminar.

The flow is characterized by Reynolds number (Re), a dimensionless parameter defined as shown in Equation 4-5.

$$Re = \frac{D \times u \times \rho}{\mu}$$

Equation 4-5: Reynolds number

D = Pipe diameter
u = Average linear velocity
ρ = Density
μ = Viscosity

At Reynolds number below 2100 it is normal to assume laminar flow, and above 4000 turbulent flow. Between 2100 and 4000 there's a transition region, where the conditions at for example the pipe entrance influence the flow to be either laminar or turbulent.

When fluid flows in a system with a stationary solid surface, as it does in most applications, a boundary layer will develop in the fluid closest to the solid surface. This is because a thin film will adhere to the surface to prevent slippage of the surface. This makes the fluid velocity at the surface zero. Viscous drag forces will cause a reduced velocity of the flow of the fluid above the surface film. The velocity will increase with increasing distance to the surface, creating a velocity gradient perpendicular to the fluid flow. The thickness of the boundary layer depends on the Reynolds number for the bulk flow (Doran 1995). Such a boundary layer is illustrated in Figure 4-1, showing the wall, the velocity gradient and the interface to the bulk phase (NASA 1971).

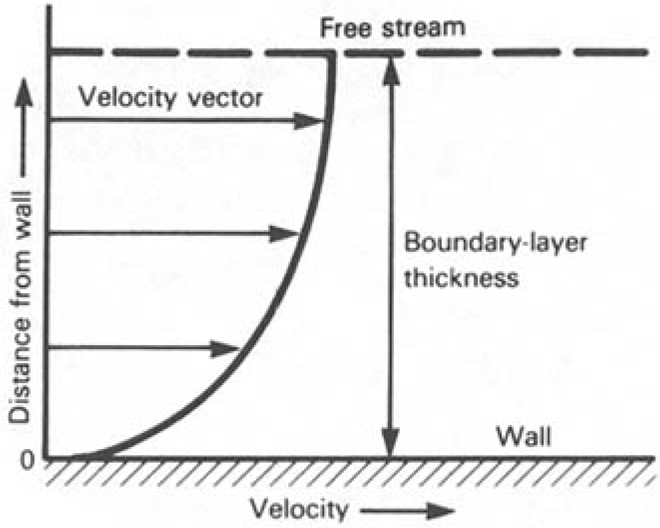


Figure 4-1: An illustration of the boundary layer, showing the velocity gradient, the thickness of the boundary layer and the interface to the bulk flow (NASA 1971).

In contraction, expansions, bends or obstacles in the flow path, normal to appear in process systems, a boundary-layer separation will occur. This happens when there's a sudden change in magnitude or direction of the fluid velocity that is too great for the fluid to keep to the surface. This will create a zone of highly decelerating fluid where large eddies or vortices will form. This zone is called the wake, and the energy needed in the wake is taken from the bulk phase giving large pressure losses in the system (Doran 1995).

4.2 Fluid properties

To produce fluid flow a shear force must be applied, referring to the definition “a fluid is a substance which undergoes continuous deformation when subjected to a shearing force”. Such a shear can be illustrated with a pack of cards, where a shear force causes the cards to slide over each other, but it may also occur in more complex systems like rotational ones (Doran 1995).

4.2.1 Viscosity

Viscosity is a dynamic property, meaning it can only be measured when the fluid is in motion. It is one of two properties used to classify fluids. The viscosity of a fluid indicates the fluids resistance to flow, representing the drag forces caused by the attractive forces in adjacent fluid layers. It can also be considered as the internal friction between the molecules, separate from that between the fluid and pipe wall.

To determine the dynamic viscosity one relates the velocity gradient in fluid to the shear force, F, necessary for flow to occur. This is done through the shear stress, which is the shear force per unit area of plate. The relationship between the shear stress, the shear force and the velocity gradient is shown by Equation 4-6.

$$\tau = \frac{F}{A} = -\mu \frac{dv}{dy}$$

Equation 4-6: The relationship between the shear stress, the shear force and the velocity gradient.

τ = Shear stress

F = Shear force

A = Area

μ = Dynamic viscosity

dv/dy = Velocity gradient

– dv/dy is denoted γ and is called the shear rate. The minus sign is there because the velocity gradient always is negative in the direction of F and therefore τ is considered to be positive (Doran 1995).

The viscosity of produced water depends on the amount of dissolved solids in the water as well as the temperature, but for most practical situations it varies from 1.5 to 2 cP at 50 ° F, 0.7 to 1 cP at 100° F, and 0.4 to 0.6 cP at 150° F. The viscosity decreases with decreasing salinity. The separation accelerates with lower viscosity of the bulk, as a lower viscosity gives lower resistance for a droplet with different density to sink or float (Arnold and Stewart 1998).

4.2.2 Density

Density is the other property used to classify fluids. The density divides fluids into two categories, compressible or incompressible, where the density is dependent and independent of pressure respectively. Gases are most often compressible while liquids are incompressible. The density of the produced water is typically in the range of 990 – 1150 kg/m^3, affected by the salinity and the temperature. The density difference between oil and water is the most important driving force in the separation process (Mator 2003).

4.2.3 Water phase salinity

Produced water contains a wide variety of inorganic compounds. The main components of the total salt concentration in produced water are chloride (Cl^-), sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}) and potassium (K^+). The total salt concentration is usually stated in % or ppm (mg/l). The salinity of produced water from an oil field is normally in the range of 3-10 %, but may exceed 20 %. For gas-condensate fields zero salinity is normal.

The water phase salinity have an impact on the electrostatic charge of the oil droplets such that water with low salinity will have a high electrostatic charge stabilizing the droplets, while higher salinity gives lower electrostatic charge which enables more coalescence (Mator 2003).

4.2.4 Interfacial tension

Oil and water are immiscible, and when mixing them together an interface is created between them. In absence of other forces a liquid droplet tends to form a spherical shape. This is caused by a tension, created by imbalance forces that the molecule sees at the interface, which exists at the boundary between the droplet and the continuous phase.

A molecule in the bulk liquid will feel the same attractive forces provided by other molecules from all directions. In contradiction, for a molecule resting at the interface, the force in the direction normal to the interface is much greater in the direction of the bulk phase than it is in the direction of the dispersed phase. The attractive force exerted by the molecules in the bulk phase upon the molecules at the interface is the interfacial tension (Doran 1995; Mator 2003).

The coalescence time tends to decrease with increasing interfacial tension, because a high interfacial tension results in droplets resisting deformation. Therefore high interfacial tension (> 30-35 dyne/cm) indicates an unstable oil-water system that will separate easily.

The interfacial tension will decrease with time, causing an increasing stability of the oil droplets the further they progress downstream the separation train. This can be explained by the ageing effect; it takes a certain time for surface active components to transfer from the liquid phase to the surface of a droplet resulting in a reduced interfacial tension (Mator 2003).

4.2.5 The zeta potential

Oil droplets dispersed in a water phase has a surface charge that is adequate to cause the droplets to repel each other. This is the electro kinetic potential, usually referred to as the zeta potential (dyne/cm). The zeta potential prevents the droplets from coalescing and keeps them dispersed.

The surface charge of the oil droplets is caused by an excess of OH^- ions at the droplets surface, creating an anionic tension. This is because the more hydrated cations will stay in the bulk phase, while the less hydrated and highly polarized anions will adsorb on the oil droplet surface (Mator 2003).

As mentioned in Chapter 4.2.3 the zeta potential is highly affected by the salinity of the produced water and Figure 4-2 shows the relationship between the zeta potential and the salinity, indicating the area where droplet growth is possible (Gramme 2009).

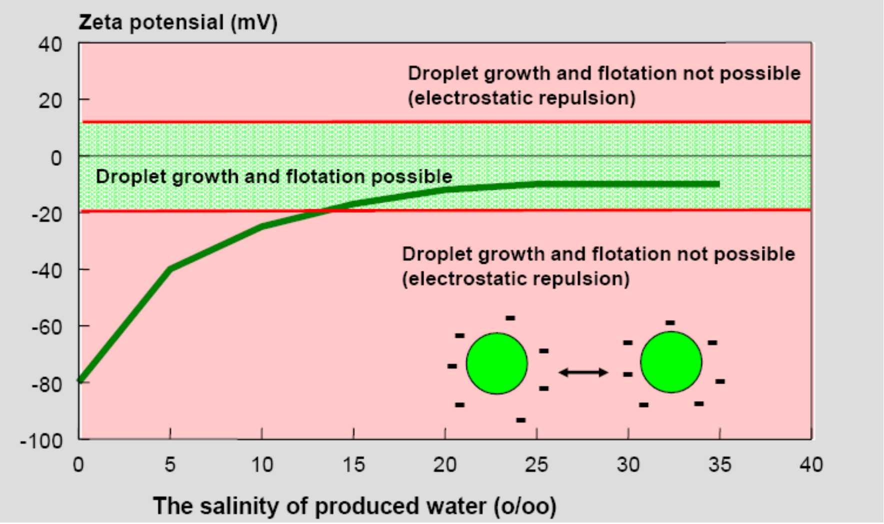


Figure 4-2: The relationship between the produced water salinity and the zeta potential, indicating the area where droplet growth is possible (Gramme 2009).

4.2.6 Solids, scale, wax, asphaltenes

Scaling is the precipitation of solid materials and can for example be a result of changes in physical conditions and water composition. Solids produced together with the petroleum and scale can dependent on the particle size and the solids relative attraction to the dispersed oil affect the produced water treatment. As an example the particles may attach to the dispersed oil, preventing the oil droplets from coalescing and complicating gravity separation as they combined could have a specific gravity similar to that of water.

Formation of wax and the presence of asphaltenes in the oil phase may have a similar affect on coalescence and the droplets ability to separate from the continuous phase (Davies, Nilsen et al. 1996; Arnold and Stewart 2008). Wax and asphaltenes are generally more common in heavier oils than in light oils and condensate.

4.3 Analytical tools and principles

When performing tests on produced water systems, it's important to perform proper sampling and use suitable analyzers. Two analytical tools and their principles are described, and some terms are clarified.

4.3.1 Sampling

Performing the sampling it's important to avoid shear forces, and this can be done through proper and adjusted sampling for the different parts of the systems. An example of this is to use a pressure cylinder when performing sampling in pressurized systems. After filling this cylinder with fluid the pressure is slowly released and the fluid is emptied into a volumetric flask. In case of high oil concentration the volumetric flask may be filled with water to dilute and stabilize the sample and with this avoid coalescence within the cylinder. This way the dilution of the sample that's measured will be known (Mator 2003).

4.3.2 Oil droplet size measurements

For particle size measurements there are different equipment and suppliers available. The principles of two common analyzers are described here.

Malvern Mastersizer is a droplet size analyzer which can be used to obtain exact information on the droplet size distribution of a dispersed phase. The measurement principle is based on laser diffraction, or light scattering. When a laser beam is passed through a sample of fluid and the beam hits a droplet or a particle, the light is scattered at an angle that is inversely proportional to the droplets, or particles, size and the light is focused by a lens to a detector.
The smaller the droplet, the larger the dispersion of the light and a sample with no droplets and no contamination will give no detectable light scattering. The results are presented graphically as a function of droplet size (Mator 2003; Malvern 2009).

Jorin ViPA (Visual Process Analyzer) is a solid particle and droplet size analyzer which can be used to decide the distribution and the content of droplets and particles in a fluid. The measurement principle is to use a digital high velocity camera to log information like numbers, size, concentration, shape factor and optical density.

The instrument can differentiate between particles, droplets and bubbles by using their differences in shape factor and optical density. The shape factor is used to distinguish the particles from the droplet/bubbles. A spherical particle like a droplet or a bubble will have a shape factor of 1 while particles that have a more irregular shape will have a shape factor of less than 1. The optical density, the degree of transparency, is used to differentiate between the gas bubbles and the oil droplets. This makes it fit for analyzing samples containing a mixture of these, like for example produced water (Dybvik 2009).

Jorin has a higher measurement domain than Malvern and misses the smallest droplets. Mator has experienced that a difference of 2-3 µm typically exists for $D_{v,\ 50}$ values (Heitmann 2009a).

The results of these types of measurements are droplet size distributions, given as curves showing the volume of oil as a function of the droplet size.

Different parameters are used to express the droplet sizes in a sample; $D_{v,\ 10}$, $D_{v,\ 50}$ (volumetric mean diameter) and $D_{v,\ 90}$. These can in general be called $D_{v,\ X}$.

$D_{v,\ X}$ is defined as a droplet size where this and all smaller droplets represent X % of the total volume of droplets in the distribution. A $D_{v,\ 50}$, which is most commonly used, of 10 µm therefore states that the summarized volume of all oil droplets having diameters of 10 µm or smaller constitute 50 % of the total volume of droplets (Husveg 2007).

In this thesis the focus has been on the smallest droplets in the distribution ($D_{v,\ 10}$ and $D_{v,\ 50}$), as these are the most difficult ones with regards to separation.

4.3.3 Oil in water concentration

The total oil concentration in produced water includes both dispersed and dissolved hydrocarbons, but most available treatment methods only aim at removing the dispersed oil.

Both Malvern and Jorin measure oil concentration (dispersed oil) while performing droplet size measurements. Other techniques exist to extract the dissolved oil and get the total oil concentration.

With the Malvern Mastersizer the oil droplet concentration is calculated by summarizing the number of detected droplets within a segment of a sample, and then multiplying this by the measured droplet size with the assumption of spherical oil droplets (Mator 2003; Malvern 2009)

Jorin reports the concentration of dispersed particles as Vppm (Visible parts per million). It's only the dispersed material that is in focus that will be accounted in the concentration measurements. Therefore can the measured concentration not be treated as a absolute value, but measurements performed with Jorin are viewed as highly repeatable, giving good results with regards to relative changes in the concentration (Dybvik 2009).

4.4 System conditions

The quality of the produced water is influenced by a number of factors. The composition is complex, and the physical and chemical properties of the produced water vary considerably depending on the geological location of the field, the characteristics of the formation it's been produced from, and the type of hydrocarbon product being produced. The properties and volume may vary between different fields, within a field, and throughout the lifetime of a reservoir (Veil, Puder et al. 2004).

4.4.1 Reservoir and oil properties

The reservoirs can consist of different types of rocks, contain different amounts of gas and liquid, and they can be gas, condensate or oil reservoirs. Details of the reservoir types aren't covered by this thesis.

The type of oil that is produced will have an effect on the oil-water separation, which depends on a certain density difference between the two phases. An arbitrary scale expressing the density or the specific gravity of liquid petroleum products was established by the American Petroleum Institute (API) (Arnold and Stewart 1998; Silset 2008; Veil and Quinn 2008). Different authors give different boundaries, but the U.S Department of Energy's (DOE) Energy Information Administration (EIA) Petroleum Navigator tool gives the following definition of the boundaries between different classes of oil (Silset 2008):

Light crude has a gravity of greater than 38° API.
Intermediate crude ranges from 22°–38° API.
Heavy crude has a gravity of less than 22° API.

As the fields age they produce increasing amounts of produced water, called increasing water cut (WC). The effect a higher WC will have on the produced water quality is influenced by other factors like the operation of the separators with regards to the water level (Heitmann 2009a). For most cases a higher WC has shown to improve the produced water quality (Willumsen 2009).

4.4.2 Production chemicals

Different kinds of chemicals are used in the production line to improve the process conditions. Many of the chemicals are surface active and will affect the oil-water interface, possibly in a way that has negative effect on the oil-water separation. Examples of negative effects of surface active chemicals are droplet stabilization or increased droplet break-up caused by reduced interfacial tension. The use of different chemicals simultaneously makes it difficult to know which the exact effects of the different chemicals. The injection of the correct dosage of chemicals is also important (Mator 2003). Appendix B gives an example of the impacts of injecting incorrect dosage of the different types of chemicals.

4.4.3 Improved recovery techniques

Different techniques are used and developed to improve the recovery of the ageing fields. In addition to creating challenges with increasing amounts of solids because of older fields, the techniques itself may affect the quality of the initial produced water. Some improved recovery techniques are:

- Artificial lift, where gas or pumps are used to bring the fluid to the surface.
- Reservoir stimulation, where acid or hydraulic pressure is used to create or reopen channels in the formation.
- Water flooding, where water is injected into the reservoir to maintain pressure.

- Gas injection, where immiscible gases is injected into the reservoir to maintain pressure.(Odland 2000).

4.4.4 Petroleum production and processing

The quality of the produced water is highly affected by the processes upstream the produced water treatment system. Figure 4-3 shows the petroleum production and processing system, with the well manifold gathering the well fluids, the choke valve regulation the flow from each well and parts of the separator train where the oil, gas and water are primarily separated.

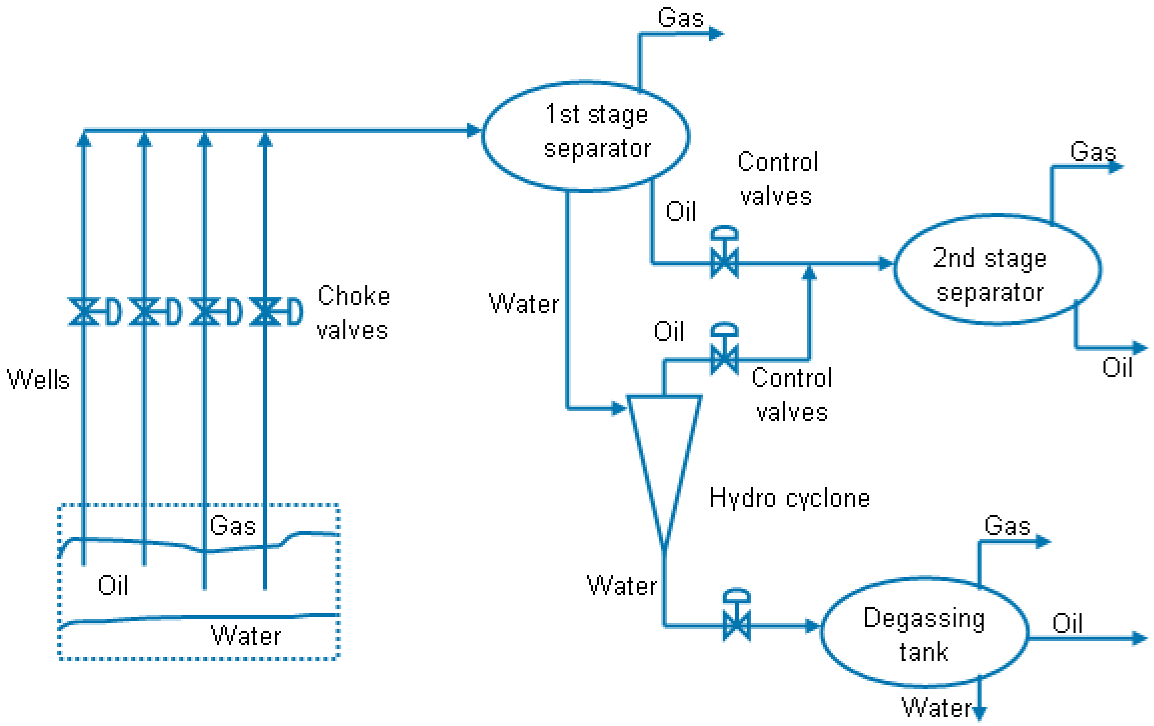


Figure 4-3: Schematics of petroleum production and processing.

The process system in Figure 4-3 shows some components known to have an effect on the oil-water separation; the choke valve, piping and the separator. These are reviewed with emphasis on their impact on produced water.

One of the purposes of the choke valve is to control the production rate, and adjusting the production rate is done by varying the pressure drop across the choke. Different types of choke valves exist, but they all share the same principle; forcing the flow through a reduced flow area. The pressure drop and the restricted flow area will create substantial shear forces in the choke causing water droplet break-up.

Gas will be liberated in shear components, as a function of the pressure drop. If the gas liberation happens simultaneously with the droplet break-up in the high shear zone of the choke, the gas bubbles may protect the water droplets from breaking. The gas bubbles may also counter coalescence within the choke. Mator (2003) states that from their experience the total effect of formation of gas bubbles in the valve is negative with regards to initial produced water quality.

After the droplet break-up in the choke the water droplets will start the coalescing process. The droplets will start colliding just downstream the high shear zone inside the choke.

The speed of the growth inside the valve may be very high and growth from 2-5 µm droplets to mm size has been experienced. The intensity of the coalescence in the choke valve may influence the oil content of the produced water, as a mechanism called multi droplet coalescence might occur. Multi droplet coalescence will cause oil droplets to be trapped in the coalescing water droplets, preventing them from separating in the downstream separators. This mechanism is believed to be dominating in determining the initial oil-in-water content of the produced water. The higher the intensity of the coalescence, the higher the content of oil-in-water will be (van der Zande 2000).

The stability of the oil-water system will have an influence on the choke valves effect on oil in water concentration. Figure 4-4 shows how the oil concentration of the initial produced water varies with respect to these two factors (Gramme 2009).

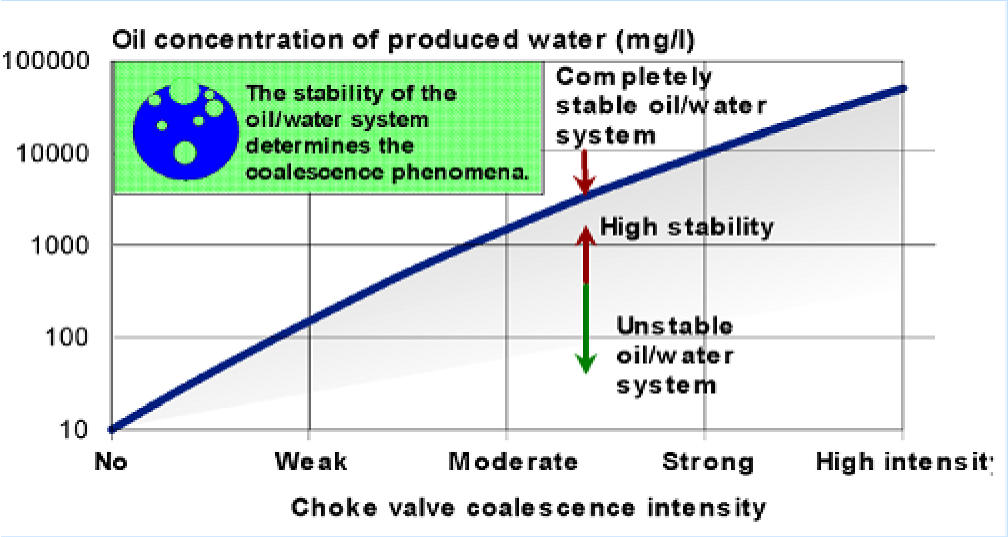


Figure 4-4: The oil concentration of the produced water as a function of the stability of the oil-water system and the intensity of the coalescence in the choke valve (Gramme 2009).

A lot of research has been performed on the droplet break-up in valves and choke valves, for instance van der Zande (2000) and Husveg (2007).

Within the pipes downstream the choke the degree of coalescence will be dependent on retention time, shear rate, concentration of dispersed phase and the initial droplet size. The growth will be slower than in the choke valve, as the energy dissipation that controls the droplet growth is much smaller in the pipes than in the choke (Mator 2003).

The separators are the once separating the main parts of the gas, oil and water. The design of a separator is essential for good separation, and different types of internals are used to increase the sedimentation area and promote coalescence. The inlet of the separator is viewed as a new peak in shear intensity (Mator 2003).

4.5 The Produced Water Treatment System

The most common equipment for primary treatment of produced water is the hydro cyclone. The hydro cyclone is normally followed by a degassing tank to release the gas that is liberated because of the differential pressure across the hydro cyclone. Figure 4-5 shows an example of a produced water treatment system.

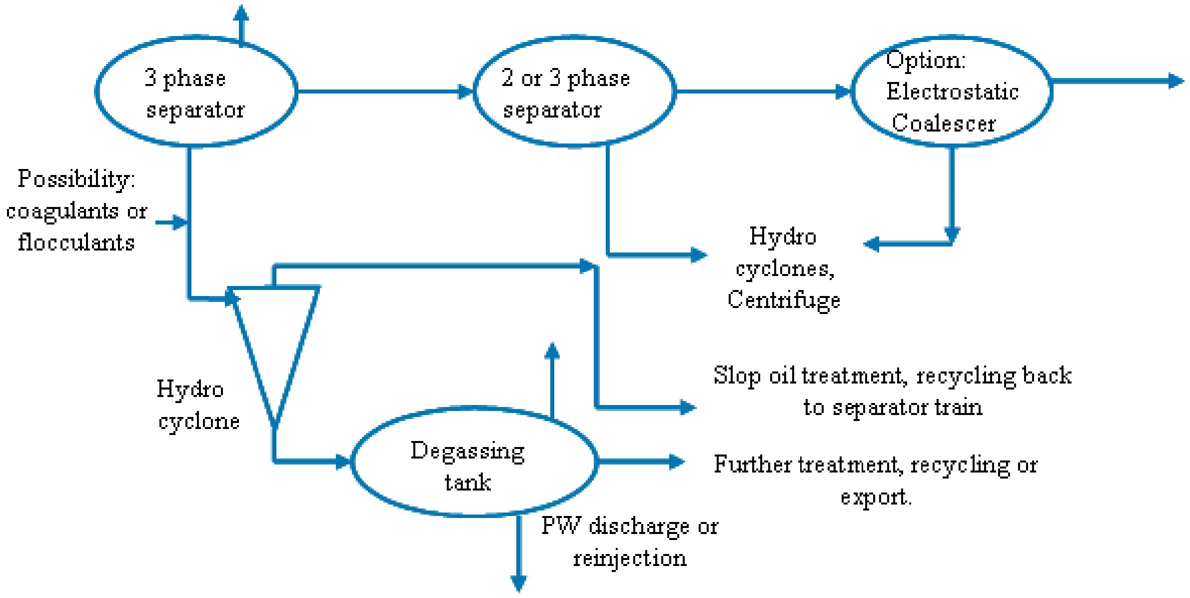


Figure 4-5: An example of a produced water treatment system.

4.5.1 The hydro cyclone

The hydro cyclone offers several advantages to other kinds of equipment, like a small footprint, lower weight, low maintenance and easy and reliable operation. The hydro cyclone also has a modular design and can be adjusted when higher flow rates are necessary (Schubert 1992).

The hydro cyclone is an enhanced gravity separator generating centrifugal forces of one thousand times the force of gravity. The fluid can enter the hydro cyclone through a tangential or axial inlet (or multiple inlets), developing a vortex system within the hydro cyclone. Two flow paths are developed, based on the density difference between the phases. There's an outer vortex moving in the underflow direction where the heavier phase exits and an inner, reversed vortex moving in the overflow direction, transporting the lighter phase (Husveg 2007; Willumsen 2009). A hydro cyclone illustration is shown in Figure 4-6 (Prosep 2009).

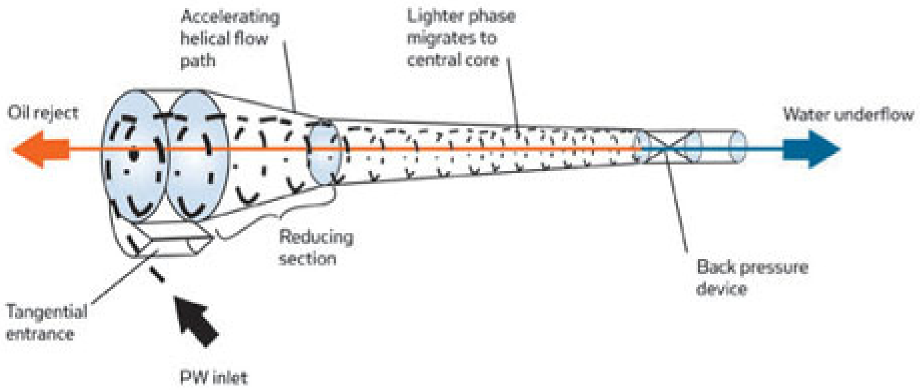


Figure 4-6: An illustration of a hydro cyclone, demonstrating its working principle (Prosep 2009).

As shown in Equation 4-3 in Chapter 4.1.1, the droplet size (diameter) in the hydrocyclone feed is important to achieve good efficiency. There are different believes regarding the minimum droplet size removed by the hydrocyclone, and 10 µm is often referred to as the limit. Mator's experience is that a good hydrocyclone with proper operational conditions can remove a larger part of the droplets larger than 5-7 µm (Willumsen 2009; Heitmann 2009a).

The energy required to achieve separation in the hydro cyclone is provided by the differential pressure across the hydro cyclone. There are different views on the differential pressure necessary. Arnold and Stewart (2008) stated that approximately 4 bars is required, while

Mator experiences that 5-6 bars is the minimum differential pressure necessary (Willumsen 2009). Factors influencing the separation in the hydro cyclones are the pressure, flow rates through the hydro cyclone, the density difference of the separating phases, the oil droplet size, oil concentration, the viscosity of the continuous phase and the reject ratio. The reject ratio is controlled by back pressure on the reject outlet stream, directly proportional to the pressure differential ratio (PDR). PDR is the ratio of the difference between the inlet and the reject outlets and the difference between the inlet and water outlet. Usually a PDR of 1.4 to 2 is desired (Flanigan, Stolhand et al. 1992; Arnold and Stewart 2008) .

Because the hydro cyclone depends on a certain differential pressure, a pump is required to pressurize the feed flow in cases where the sufficient pressure isn't available. Pumps are further reviewed in Chapter 4.5.2.

The hydro cyclone is sensitive to solids, which can cause the liners to clog or erode pending on the nature of the solids. Even though some of the solids are removed in the separator, some amounts of solids are likely to follow the flow to the produced water system. Because of this a desanding cyclone could be installed upstream the hydro cyclone. The desanding cyclone is further reviewed in Chapter 4.5.3.

4.5.2 Pumps

One definition of a pump is that it is a device that moves and raises the pressure of a liquid. Many varieties of pumps and pump classification systems exist.

A basic system of classifying pumps is first to define the principle by which the energy is added to the fluid, then identify the means of which the principle is implemented and finally identify the specific pump geometries.

This first separates the pumps into two major groups, the dynamic (also called kinetic) and the displacement pumps. Dynamic pumps add the energy continuously to increase the velocity of the fluid to values greater than those occurring at the discharge side such that the reduction in velocity within the pump creates a pressure increase. Displacement pumps add energy periodically by applying force to one or more movable boundaries of any number of closed, fluid- containing volumes, creating an increase in pressure up to the value that is required to move the fluid through valves or ports into the discharge line.

Dynamic pumps can further be divided into varieties of centrifugal pumps or special-effect pumps. The displacement pumps are classified further into reciprocating or rotary pumps, depending on how the pressure-producing members move. The reciprocating pumps increase the liquid energy by a pulsating action, while rotary pumps don't create pulsation. These pump types are further divided based on geometric differences. Figure 4-7 gives an overview of different pump configurations and how they are categorized (Forsthoffer 2005; Karassik, Messina et al. 2008). Within this thesis, the centrifugal pumps and some subdivisions of rotary pumps are dealt with the most. These are marked with blue in Figure 4-7.

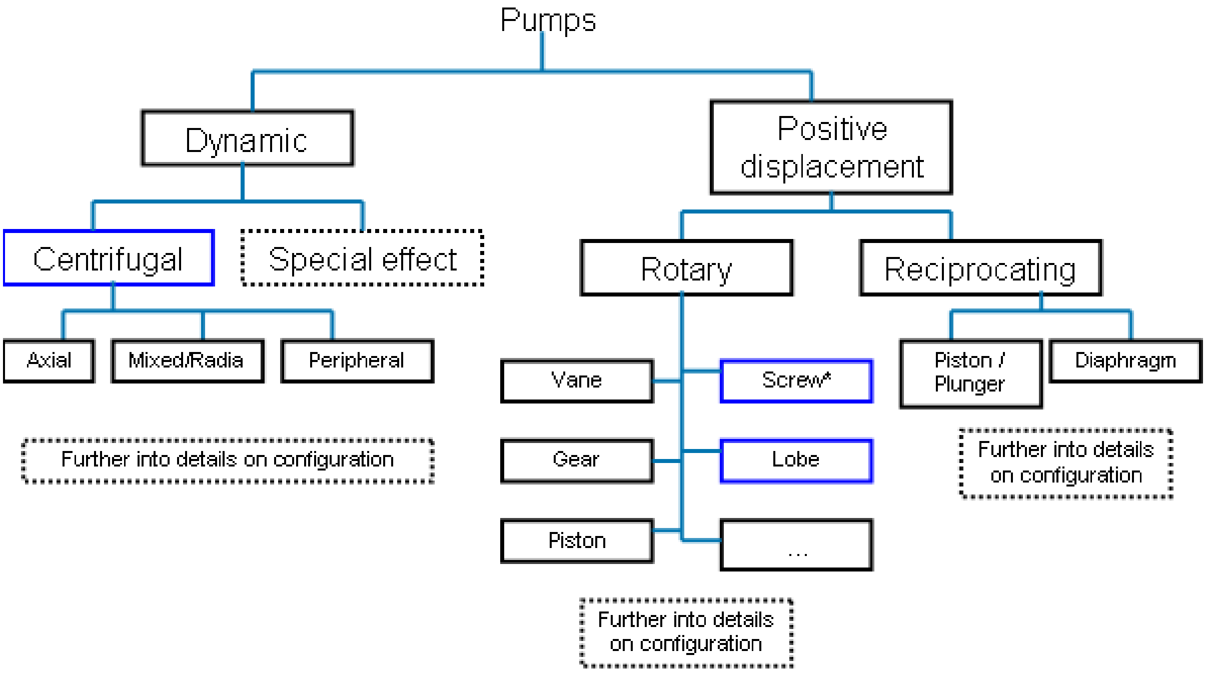


Figure 4-7: Overview of the main pump configurations. The blue boxes show the pumps dealt with the most in this thesis. * Single-screw pumps are often called progressive cavity pumps or eccentric screw pumps (Karassik, Messina et al. 2008).

It's referred to Appendix C for more detailed figures regarding the further classification of the centrifugal and rotary pumps, as given by the Hydraulic Institute and approved by the American National Standards Institute as national standards. Some differences may occur between Europe and America with regards to classification.

In this thesis the centrifugal pump, variations of the screw pump and the lobe pump are mentioned. Some information regarding these types follows:

The centrifugal pump works such that liquid enters the center of the rotating impeller which imparts energy to the liquid. Then the centrifugal force discharges the liquid through a volute, as shown in Figure 4-8. Single and multi stage centrifugal pumps exist.

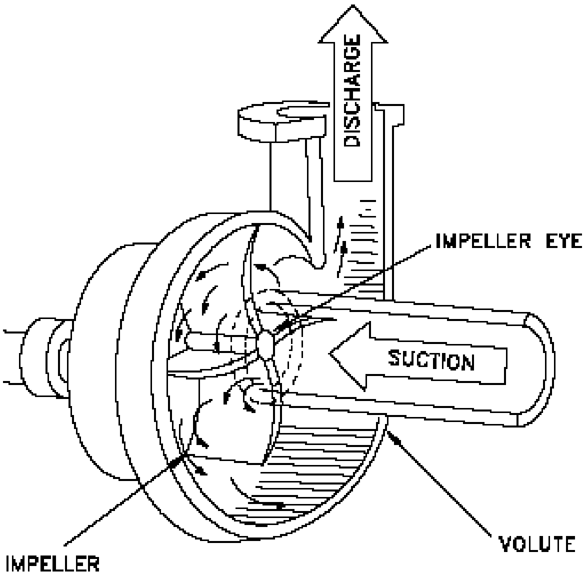


Figure 4-8: A simple schematic of a centrifugal pump (Engineers Edge 2009).

The screw pumps are generally classified into single- or multiple rotor types. Single- screw pumps are often called progressive cavity pumps or eccentric screw pumps, the latter used in this thesis. Multi-screw pumps exist in many configurations and designs. Generally for the multiple screw pumps, the fluid is carried axially between threads of two or more close clearance rotors so that a fixed volume of fluid is displaced with each revolution. Figure 4-9 shows a sketch of a two screw pump (Hydraulic Institute).

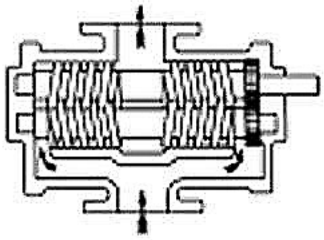
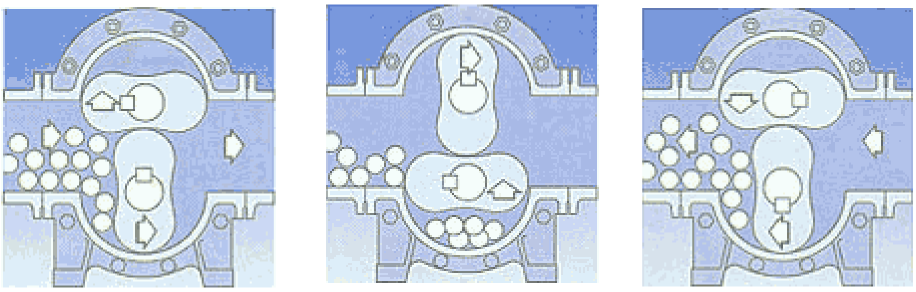


Figure 4-9: A simple schematic of a two screw pump (Hydraulic Institute).

The lobe pump got its name from the rounded shape of the rotor radial surfaces that permits the rotors to continuously overlap each other as they rotate. Lobe pumps can be either single or multiple lobe pumps, and are further classified with regards to configuration and design. Figure 4-10 shows an example of a lobe pump, as well as the principle (Vogelsang Germany).



0° position: Conveying via the upper lobe. Seal against backflow via the lower lobe.

90° position: Conveying via the lower lobe. Seal against backflow via the upper lobe.

Reverse flow: Reversing the flow direction by changing the rotating direction of the drive shaft.

Figure 4-10: An example of a lobe pump, and the principle of this type of pump (Vogelsang Germany).

For further information regarding pump classification and the different pump types, it's referred to (Nelik 1999; Nelik and Brennan 2005; Volk 2005).

The operation of pumps is important when it comes to shearing. Mator's experience with regards to pumps is that there is a larger risk of droplet shearing using centrifugal pumps than screw pumps. They state that the rotational speed on the centrifugal pump also will affect the shearing and that a low rpm is preferred. Figure 4-11 shows an example of how the rotational speed of a centrifugal pump affects the droplet size distribution, with decreasing rotational speed increasing the droplet sizes (Gramme 2009).

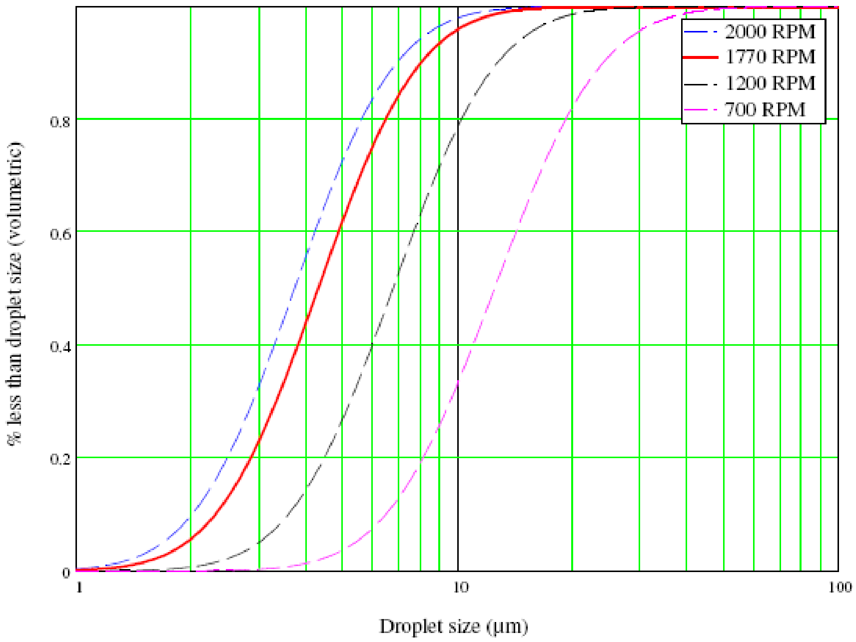


Figure 4-11: The effect of the rotational speed of a centrifugal pump on the oil droplet size distribution, with increasing rotational speed from right to left (Gramme 2009).

With regards to screw pumps, shearing has been observed with high $D_{v,\,50}$ upstream the pump, but with an acceptable droplet size after shearing (40 µm to 22 µm) (Finborud 2009).

Chapter 6.1 offers a further review of literature concerning pumps and their effect on oil droplets.

4.5.3 The desanding cyclone

The desanding cyclone has long operating experience from other industries and is now the most used equipment in the offshore industry for removal of solids. Desanding cyclones are simple, as there are no moving parts. The size of the liners within the desanding cyclone determines the size of the solids that can be removed, and with small liners solids down to 5 µm can be removed. The desanding cyclone can be used for very high pressures, and a typical differential pressure over the desanding cyclone is 1-5 bar (Grov 2007; NATCO 2007).

The desanding cyclone is also referred to as a solid-liquid hydro cyclone and has a common flow structure with the liquid-liquid hydro cyclone which in this thesis is referred to simply as the hydro cyclone. As with the hydro cyclone the fluid enters the desanding cyclone through a tangential inlet, and develops a vortex system within the cyclone. Two flow paths are developed, based on the density difference between the phases. There's an outer vortex moving in the underflow direction where the heavier phase exits and an inner, reversed vortex moving in the overflow direction, transporting the lighter phase (Husveg 2007). Before the rotation and the decreasing diameter forces makes the liquid turn and enter the inner vortex, the liquid moves in a downward spiral flow along the wall (Lohne 1994). Figure 4-12 shows a simple illustration of a desanding cyclone, where the solids is the heavier phase and the liquid is the lighter phase (Merpro).

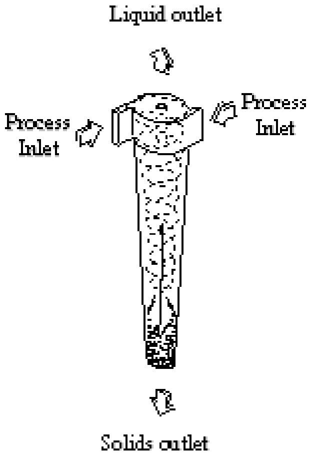


Figure 4-12: Simple illustration of a desanding cyclone (Merpro).

Husveg (2007) reported from work by Smyth and Thew from 1987, that there are regions within a hydro cyclone that experience higher energy dissipation rates per unit mass (ε) than the overall average and that this affects the prediction of droplet break-up. Looking at dewatering hydro cyclones Sinker and Thew concluded in 1996, that near wall regions of a hydro cyclone experience high turbulence and large viscous shear rates, hence energy will be dissipated. It seems to be commonly recognized that the inlet region create the highest shear forces and energy dissipation rates ($\dot{E}$) (Husveg 2007). Desanding cyclone geometry resembles the geometry of the dewatering hydro cyclone, and it can therefore be assumed to have the same high shear regions (Husveg 2009). Generally inside a desanding cyclone or a hydro cyclone, the shear rates will depend on the actual flow path. High shear forces have been reported to exist in the outlets and downstream the outlets of such equipment as well, as the departing vortex will decelerate and break (Husveg 2007).

The desanding cyclone may have several application possibilities in the process and produced water treatment system. It can be located prior to the 1st stage separator, downstream the 1st stage separator prior to the hydro cyclone, at the jet water drain lines from the separators and in the treatment system prior to re-injection of produced water to mention some. Well head desanders are also a possibility, removing solids prior to production.

Chapter 7.1 offers a further review of literature concerning desanding cyclones and their effect on oil droplets.

5 Methods

To reach the goals stated in Chapter 1.2, different methods were applied. Parallel methods were applied to both the part about pumps and the part about desanding cyclones. Thus this chapter covers both topics.

To reveal tests that had been performed previous to this thesis and to get an insight of the common perceptions of using pumps and desanding cyclones for this application, a literature survey was executed. Different databases were used and these are presented in Table 5-1.

Table 5-1: An overview of the databases that were used during the literature survey for pumps and desanding cyclones.

Name of database	Type of database
Scopus	Abstract and citation
Knovel	Full text
SPE eLibrary	Papers from SPE sponsored conferences
Compendex	Abstract and citation
ETDEWEB	Citation and full text
OTC – OnePetro	Papers from OTC sponsored conferences
Bibsys Ask	Library database
Bibsys Mime	Covers multiple databases
Bibsys Tyr	Magazine database

People within the StatoilHydro system were contacted, as well as some former employees, to try to derive information and tests that could have been contained within the system.

To discover if other oil companies had performed research or had experience to share on this topic, other oil companies were contacted.

Several suppliers of pumps and desanding cyclones were contacted to acquire their experience and their knowledge. The results of this research are presented in Chapter 6.1 for pumps and Chapter 7.1 for desanding cyclones.

A complete list of these contacts is found in Appendix D.

A list of literature that has been reviewed without giving results or being cited are given in Appendix E to ease later surveys related to these topics.

In connection with scheduled offshore trips made by Mator to perform troubleshooting and optimizing of the produced water treatment systems, some tests concerning this thesis were implemented. This applies to Cases 2 and 5. For Case 2 a test program for the measurements regarding this thesis was made, and is included in Appendix F. With Case 5, Mator planned and performed extra tests with regards to this thesis.

There was also attempted to have new oil concentration measurements performed in relation to the desanding cyclone on Case 1, but this wasn’t possible at the period of this thesis. The test program that was made is included in Appendix G.

The results from the offshore tests are presented in Chapter 6.2 for pumps and Chapter 7.2 for desanding cyclones.

6 Pumps

In this chapter the information regarding pumps acquired during the literature survey, contacts with the suppliers, and the reports from the offshore tests are presented. The chapter ends with a discussion of the presented results, and a recommendation for further work.

6.1 Literature survey

Suppliers of pumps for produced water treatment systems were contacted regarding their experiences concerning shear and coalescence of oil droplets, and which pump types they recommend and deliver for this application.

Bjørge AS give the following ranking for the pump configurations they deliver for the purpose of boosting low pressure produced water with regards to the shearing effect on oil droplets:

1. Eccentric screw pumps
2. Twin screw pumps
3. Piston pumps, reciprocating or rotating
4. Centrifugal pump

Bjørge AS stated that different eccentric screw pumps give various degree of shear because of different internal designs (eccentricity, number of stages, length of pitch etc), but that the principle of eccentric screw pumps are the best. They said that in addition to the differential pressure, the rotational speed is important when it comes to shearing. Bjørge AS recommends eccentric screw pumps, but they have delivered centrifugal pumps on request.

Axflow prefers to deliver ARC lobe pumps for boosting low pressure produced water because they find that they are better with regards to maintenance. Their experience is that the ARC lobe pumps are just as gentle towards the flow as the eccentric screw pumps. Axflow don’t recommend using centrifugal pumps for this application as they view it as not being gentle to the flow.

PG Marine Group - Ing Per Gjerdrum AS stated that the eccentric screw pump has been the most obvious choice when low shear is preferable. They said that the dispersion created by the centrifugal pump increases with increasing power number, which is a function of rotational speed, impeller diameter and so on. They also said that reciprocating pumps never have been viewed as low shear because their configuration is viewed as a set of check valves. With regards to rotating displacement pumps they stated that they will all have a certain back flow that will be subjected to shear. They referred to research performed by Norsk Hydro in the 80’s and 90’s that showed that displacement pumps gave less droplet break-up than centrifugal pumps and another study where they were told that the use of screw pumps instead of centrifugal pumps led to a 50 % reduction of the oil concentration in the produced water discharge.

Seepex have a long history of delivering progressive cavity pumps (eccentric screw pumps) to produced water systems. Seepex stated that their experience is that these pumps are low shear design. Emulsions have never been a problem when supplying these pumps into such systems. Their pumps are in use both in hydro cyclone feed and in reject oil back to the separator. Integration of progressive cavity pumps offshore can be a challenge as the design tends to be long in dimension and takes up a large footprint when comparing throughputs with other pump technologies. Pumps to deliver 200m^3/hr for example can be as long as 6000mm. Seepex are interested in performing tests to confirm and document the low shearing of their pumps.

Cyclotech deliver produced water treatment packages, and when implementing pumps they use centrifugal pumps with closed impellers and high hydraulic efficiency, running at half speed. They might consider changing to Disc flow pumps which are said to be low shear, but the negative with these are low hydraulic efficiency.

In performing the literature survey it was discovered that little work has been performed on pumps and their effect on oil droplets in produced water. Two studies by Flanigan et al from the late 80's and early 90's was however found.

In the beginning of drop size analysis being used as a tool, Flanigan et al (1988) performed work on evaluating different measurement devices and sampling methods. At the same time they performed actual field testing of pumps, valves and strainers. Following the results from the pump experiments are presented.

The study used a once-through oily water test circuit, Figure 6-1, and actual produced fluids from production wells under normal operating conditions. The separator with residence time of 4-8 minutes was used to separate free oil and gas thereby simulating typical produced water conditions. Different valves on the separator outlet made it possible to vary the concentration and droplet sizes to the test system. Once passing through the test circuit the fluids are recycled back to the gun barrel.

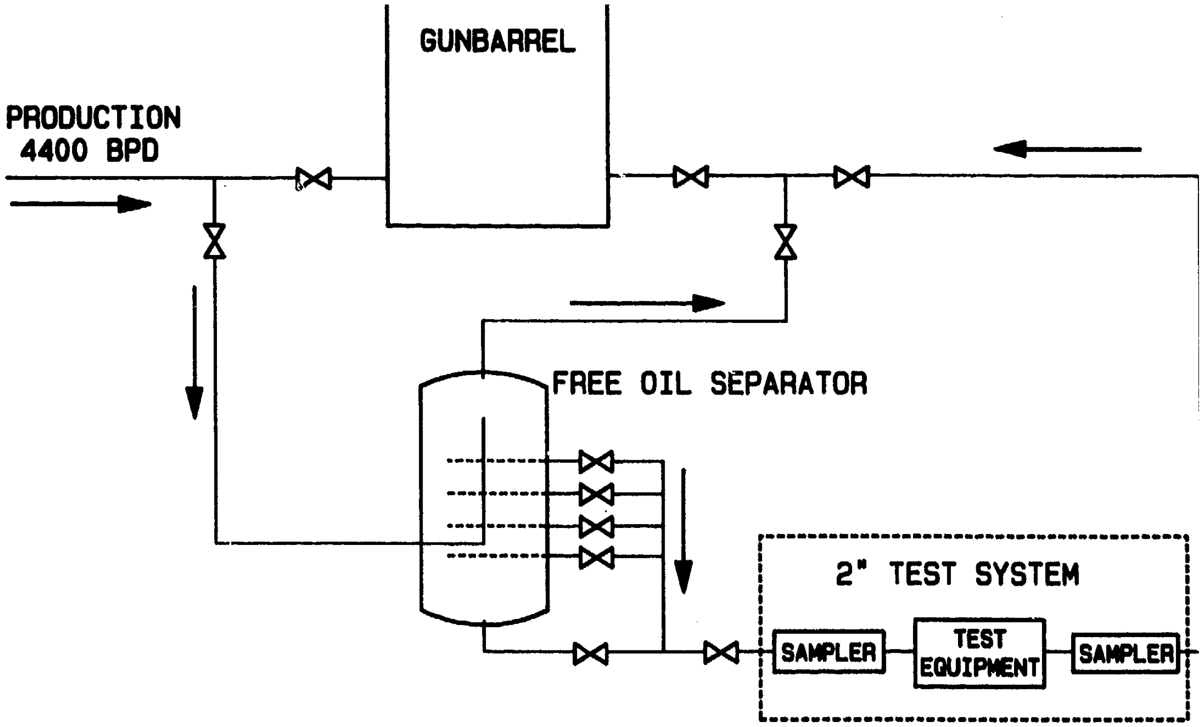


Figure 6-1: Schematics of the once through oily water test circuit, showing the gun barrel, the free oil separator with the different outlet valves, and the test system with the test equipment and samplers (Flanigan, Stolhand et al. 1988).

The crude oil in the experiment had a density of about 36 °API gravity at 60 °F (15.5 °C). During the experiment the fluids kept 117 °F (47 °C). The produced water density was about 9.3 °API at 110 °F (43 °C), with a 90 % water cut and an oil concentration of 100 to 550 ppm. The separator pressure was between 5-10 psig**.**

The isokinetic method was the only sampling method that obtained a representative sample, and therefore only the droplet measurements from this method were used to evaluate the equipment. The construction of the isokinetic sampling method is shown in Figure 6-2.

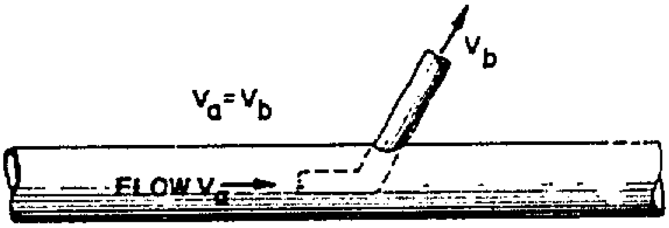


Figure 6-2: Isokinetic sampling method, with constant velocities (Flanigan, Stolhand et al. 1988).

The authors stated that although there were uncertainties to the accuracy of the measured sizes, the measurements were precise enough to be repeatable. They also stated that the trends of the droplet sizes were more important than the actual droplet sizes.

The testing of a twin lobe pump under varying operating conditions showed that at constant differential head the outlet mean droplet size increased with increasing pump flow rate. The authors stated that this trend was seen for all the positive displacement pumps. The test results of the twin lobe pump test are shown in Figure 6-3.

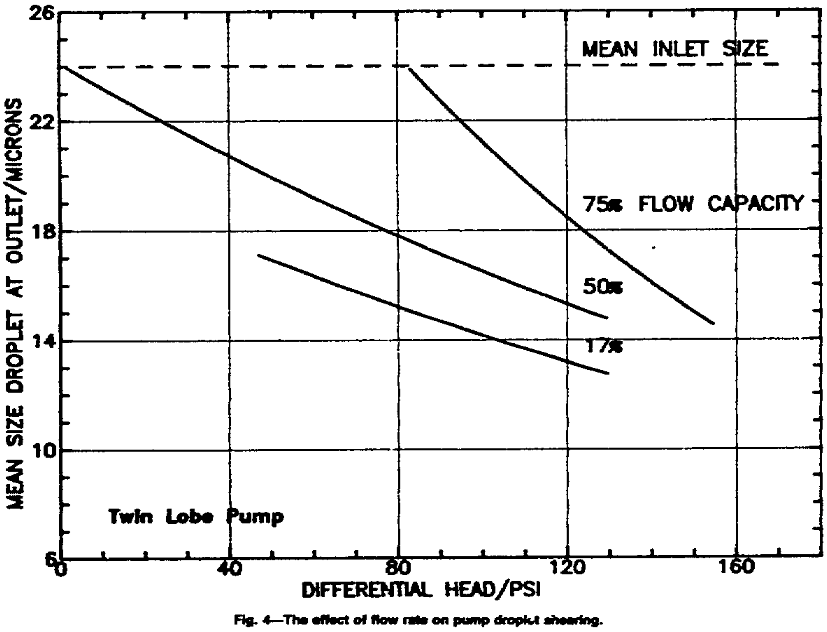


Figure 6-3: The effect of flow rate on pump droplet shearing. The curves show the mean droplet size at the outlet of the twin lobe pump as a function of flow capacity at constant differential heads. Mean inlet droplet size at the tests was 24 µm (Flanigan, Stolhand et al. 1988).

The test showed oil droplet break-up over the pump for all capacities and differential heads.

When choosing test pumps Flanigan et al (1988) found no manufacturer with data to demonstrate the effect of a pump on the droplet size distribution, even though some pumps were stated to be low shear design or capable of running in low shear mode. Flanigan et al tested seven different pumps representing five pump types and ranked them based on their effect on the droplet size where number 1 showed the least break-up:

1. Progressive cavity pump
2. Twin lobe pump
3. Sliding rotary pump
4. Single stage centrifugal pump
5. Twin screw pump

The results given in Figure 6-4 show that all pump types tested showed consistent droplet break-up. The curves in Figure 6-4 represent the best operating conditions for the pumps.

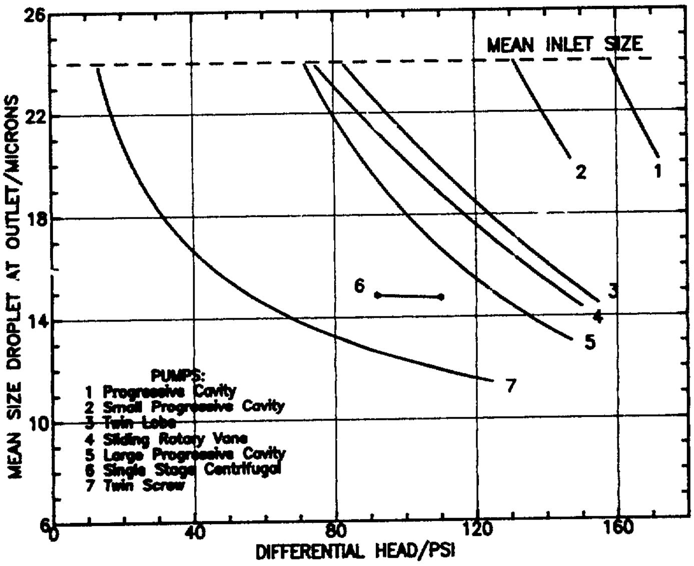


Figure 6-4: The effect of differential head on pump droplet shearing. The curves show the mean droplet size at the outlet of 7 different pumps as a function of the differential head. Mean inlet droplet size at the tests was 24 µm (Flanigan, Stolhand et al. 1988).

The progressive cavity pump showed the least droplet shear over the greatest pressure range.

Flanigan et al (1992) continued their research on pumps with new experiments on the performance of low-shear pumps and the performance of the downstream hydro cyclones, both onshore and offshore. As the progressive cavity pump gave the least shear in the previous tests (Flanigan, Stolhand et al. 1988) this pump type was used in these experiments. For the onshore test, the once-through oily water circuit shown in Figure 6-5 was constructed. The circuit resembles the one in the previous experiment, with the exception of the hydro cyclones situated downstream the pump.

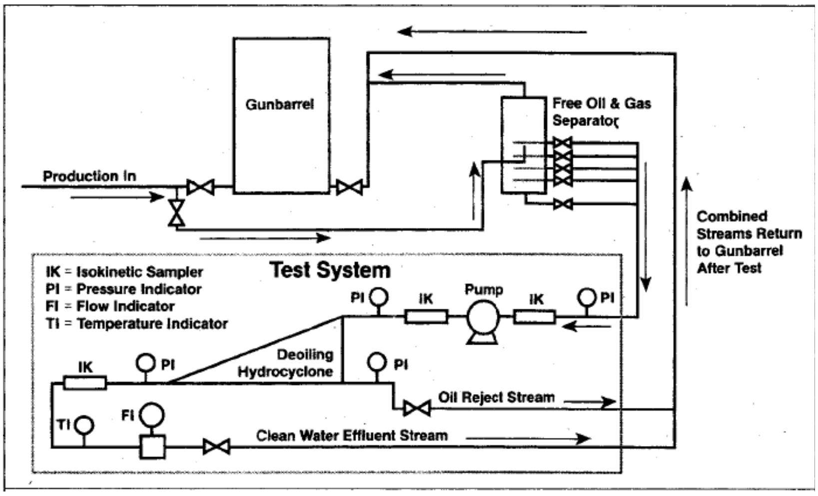
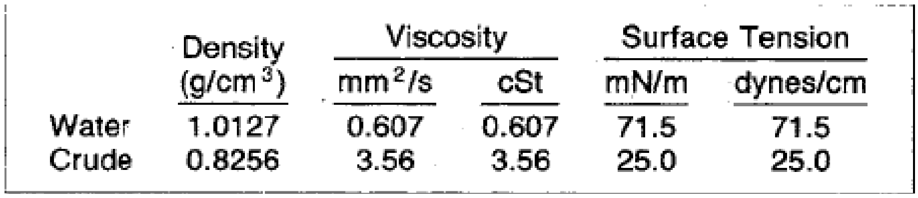


Figure 6-5: The once-through oily water circuit constructed for the onshore tests (Flanigan, Stolhand et al. 1992).

Sampling points were located upstream and downstream of the pump and downstream the hydro cyclones, marked isokinetic samplers (IK) in Figure 6-5.

Actual produced fluids from production wells under normal operating conditions were used, with no significant concentrations of gas or suspended solids in size range that would influence the measurements. The separator with residence time of 4-8 minutes was used to separate free oil and gas thereby simulating typical produced water condition. Different valves on the separator outlet made it possible to vary the concentration and droplet sizes to the test system. Once passing through the test circuit the fluids are recycled back to the gun barrel. Droplet size measurements were made from the system consisting of a progressive cavity pump and two different size hydro cyclones. Presented here are mainly the results concerning the pumps effect on droplet size, but also some results from the hydro cyclone showing the way the pump affects the downstream equipment.

During the experiment the temperature of the production fluids was 117 °F (47 °C). The fluid properties in the onshore test are shown in Figure 6-6. The production fluids averaged a 90 % water cut and the produced water had an oil concentration of 100 to 550 ppm. The separator pressure was between 5-10 psig**.**



	Density	Viscosity		Surface Tension	
	(g/cm^3)	mm^2/s	cSt	mN/m	dynes/cm
Water	1.0127	0.607	0.607	71.5	71.5
Crude	0.8256	3.56	3.56	25.0	25.0

Figure 6-6: Overview of the properties of the crude oil and the produced water of the fluid used in the offshore test (Flanigan, Stolhand et al. 1992).

The progressive cavity pump was operated with a differential head of 175 psi (~12 bar), generating a much higher pressure than required by the hydro cyclone. Figure 6-7 give the droplet size distribution curves attained in this test.

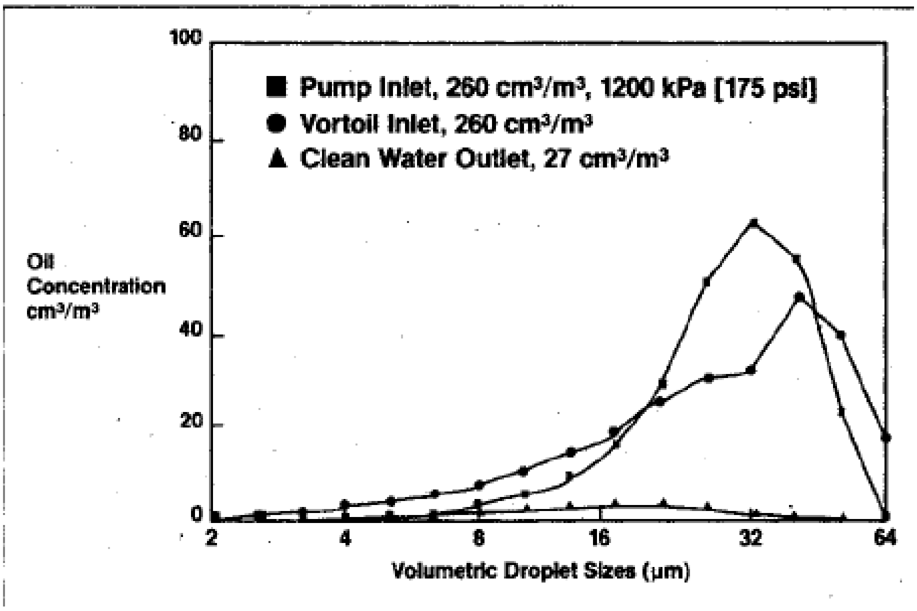


Figure 6-7: Droplet size distribution curves from the inlet of the pump, the inlet of the hydro cyclone (vortoil) and the outlet of the hydro cyclone (clean water outlet) (Flanigan, Stolhand et al. 1992).

Figure 6-7 shows that the larger droplets were broken into smaller droplets by the pump, increasing the concentration of oil drops smaller than 16 µm. In this particular case the hydro cyclones efficiency was about 90 %, with 260 ppm in the inlet and 27 ppm in the outlet flow.

The offshore test was performed to validate the conclusions from the onshore test. Figure 6-8 shows the offshore test system. The system includes a by-pass of the pump from the produced water flash tank to the hydro cyclones, to test the efficiency of the hydro cyclone with and without pumping. A large progressive cavity pump rated for 3180 m^3/d was chosen for the experiment to make it possible to eventually feed a four-in-one hydro cyclones unit.

The pump was run at constant speed, with a possibility of recycling effluent from the hydro cyclones to the flash tank.

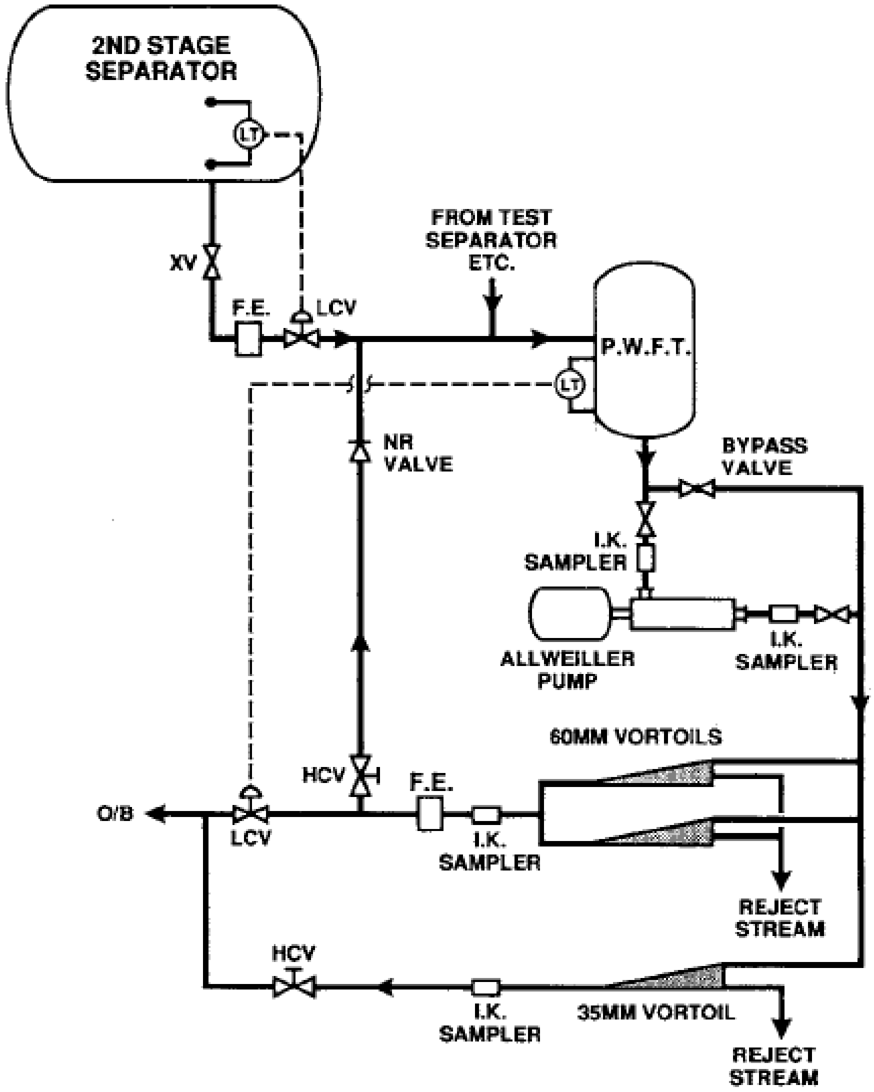


Figure 6-8: The offshore test system with a large progressive cavity pump installed (Flanigan, Stolhand et al. 1992).

The oil and water densities of the produced fluids were respectively 0.834 and 1.020 g/cm^3 at 158 °F (70 °C). The test conditions onshore and offshore were by the authors evaluated to be comparable.

During the test the differential head on the pump was varied. The differential head ranged from 58 to 111 psi (4 - 7.65 bars) while the maximum discharge pressure was about 149 psi (10.3 bars). The sampling points were located upstream and downstream the pump and downstream the hydro cyclones, marked IK sampler in Figure 6-8.

During the tests the inlet mean droplet sizes of the pump ranged from 11 to 17 µm. Comparing these values to the outlet mean droplet sizes of the pump, the mean ratio droplet size over the pump was greater than 0.95. The authors therefore concluded that no significant droplet shearing was observed.

The recycling of the clean water effluent (from the hydro cyclone) caused an expected decrease in the oil concentration at the hydro cyclone inlet, but also a decrease in the mean droplet size from 16.4 to 12 µm. A recycling of 70 % of the effluent was necessary to obtain the desired efficiency of 90 % or the requirements of 40 ppm oil concentration. The authors stated that the tests indicated that a constant speed pump recycling the effluent achieved enhanced performance and flow control.

In addition to the experiments mentioned, a test was performed with total recycling of the hydro cyclones (60 mm), with reject and clean- water discharges closed. Only the 60-mm hydro cyclones were on-line during the test.

The results of this test are shown in Figure 6-9, with the normalized volume percent of oil as a function of droplet size.

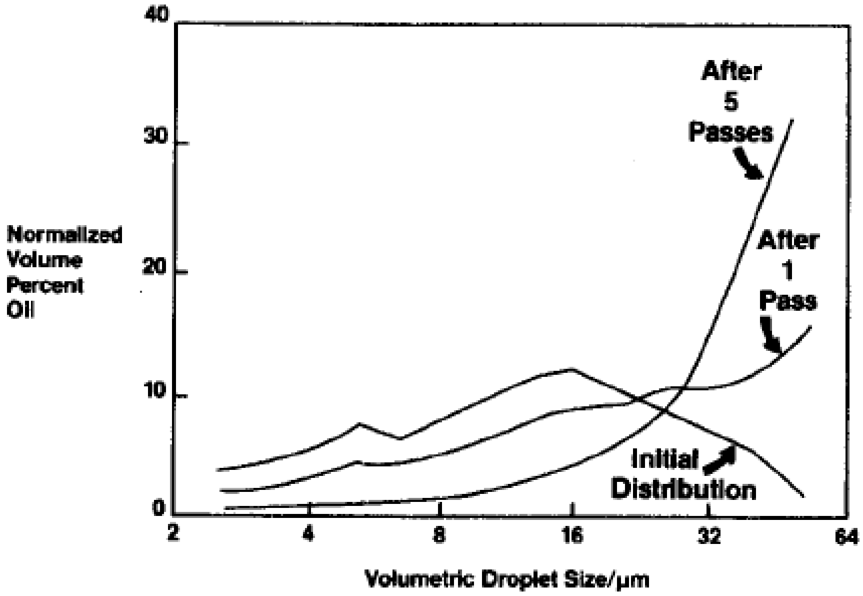


Figure 6-9: Droplet size distribution curves for the recycling of the flow through a hydro cyclone, showing the initial distribution, and the distribution after one and five passes through the hydro cyclone (Flanigan, Stolhand et al. 1992).

The droplet size distribution after 0, 1 and 5 passes through the system showed an increase of the mean droplet size from 14 µm to >30 µm after 5 passes. Reaching the mean droplet size of >30 µm the share of smaller droplets had decreased radically.

The authors stated that this indicated coalescence in the hydro cyclone and confirmed the low-shear operation of the progressive cavity pump.

Schubert (1992) referred to testing performed to determine the optimal design of a centrifugal pump for low shear operation. This test found that low shear operation of a centrifugal pump could be obtained by limiting the pump head and correctly select the involute type, diameter and RPM. The test also showed that to minimize the shear the centrifugal pump is best operated at constant flow. During this test both pressure and speed were varied to find the optimum operating conditions.

The droplet size across the pump at different flow rates was measured showing droplet break-up in the 25 µm range (inlet/outlet ratio of 0.75-0.8), but negligible reduction in 5 µm droplets. Schubert also referred to an onshore application test stating that a reduction in the oil concentration over the hydro cyclone from 300-500 ppm to 20 ppm is a clear indication of low shear in the centrifugal pump.

Ditria and Hoyack (1994) stated that the pump selection and operation of the pump are equally important. They reported that positive displacement pumps provide low shear characteristics, but that centrifugal pumps may do so as well when properly sized and correctly used. The authors reported that a centrifugal pump with closed impeller design should be selected and operated at a hydraulic efficiency above 70 % and a maximum speed of 1800 rpm.

According to Ditria and Hoyack (1994) both single-stage and multi-stage centrifugal pumps may be used to raise the pressure in a produced water system. They stated that a single stage centrifugal pump operated at maximum differential pressure of 80 psig (5.5 bars) will cause minimum droplet break-up when the hydraulic characteristics of the pump and the total number of hydro cyclone liners are correctly matched.

The executive summary of a report regarding testing of pump solutions for hydro cyclone feed was provided by Opus. The tests evaluated the oil droplet shearing characteristics of four different feed pumps; the progressive cavity, the single and multi stage centrifugal, and the lobe pump, using crude oil with density of 36 °API in seawater at 55 °C.

The main results reported from this testing was the following (Environment & Resource Technology Ltd 1996):

- The progressive cavity pump was proven most suitable as it was shown to promote coalescence at all feed conditions assessed in the test programme.
- The centrifugal pumps showed that correct operation could minimize and eliminate shearing of oil droplets. The efficiency was proven as a key factor, with decreasing efficiency giving increasing amount of shear.
- Multi stage pump proved better than single stage testing at comparable discharge heads, implying that shear reduces if the head is generated across several stages rather than a single stage. Reduced rotational speed of the multi stage pump was shown beneficial as well.
- The lobe pump showed variable degree of shear depending on the feed conditions, and was shown suitable for this application under certain feed conditions.
- Increasing oil concentration resulted in decreasing degree of shear, and at a concentration of 500 mg/l (ppm) all pump designs was shown to promote coalescence.
- Increasing median droplet size (15-30 µm) gave an increasing degree of shear.
- Reducing the temperatures (12 °C and 30 °C) reduced the degree of shearing.

The report states that all the pumps were proven suitable for pumping the hydro cyclone feed at some feed condition, but the progressive cavity pump proved to be the best for all feed conditions.

A Shell paper presented at the 6th Produced Water Workshop regarding Shell's water treating experience in the deep waters of the Gulf of Mexico (Walsh 2008) was provided by Petreco Process Systems (part of Cameron). Shell referred to two cases of trying to implement low shear pumps:

1. Replacing a centrifugal pump with a recessed impeller type centrifugal pump with a larger impeller that rotated at a lower specific speed (10 inch – 3550 rpm to 13 inch 1200 rpm).

The new pump increased the droplet shear and the report states that a recessed impeller pump will create greater shearing because it allows the fluid to churn and recycle within the pump. This recycling also gives the pump a lower efficiency.

2. Installing twin screw pumps to minimize the shearing of the oily water from the wet oil tank. The experience of the offshore personnel was that the standard centrifugal pumps didn’t shear fluid significantly more than the twin screw pumps. A lot of operational and maintenance problems was experienced with the twin screw pumps.

The paper also presents Shells guidelines for the design of a low shear centrifugal pump:

- Slow speed (< 1800 rpm)
- High hydraulic pump efficiency (> 70 %)
- Large impellor diameter (goes along with slow speed for given gpm)
- Large discharge nozzle (slow discharge speed)
- Limited pressure boost per stage (< 50 psi)
- Low specific speed Ns < 700

6.2 Offshore experiments

Internal reports from offshore tests related to troubleshooting and optimization of the process system and the produced water treatment system at offshore platforms, have supplied this thesis with test data from real conditions. Case 4 was an external report performed and documented by CETCO Oilfield Services Company. Mator AS has performed all the other tests and written the following reports. The data available for booster pumps are presented and evaluated in the following chapters.

6.2.1 Centrifugal pumps

This section covers the test results available for the centrifugal pumps. The different tests are denoted as Case X (X=1, 2, 3...). The complete overview of the test data including operational data of the different cases is found in Appendix H.

6.2.2 Case 1

The oil in Case 1 is a medium light (30-40 ° API), waxy crude oil.

Case 1 has a process system with a separation train withstanding of three separation steps. The produced water treatment system is shown in Figure 6-10, with a desander cyclone, a hydro cyclone, and a degassing tank. The produced water from the electrostatic coalescer outlet is pumped to the outlet of the 1st stage separator by a single stage centrifugal pump from 2.2 barg to 14 barg.

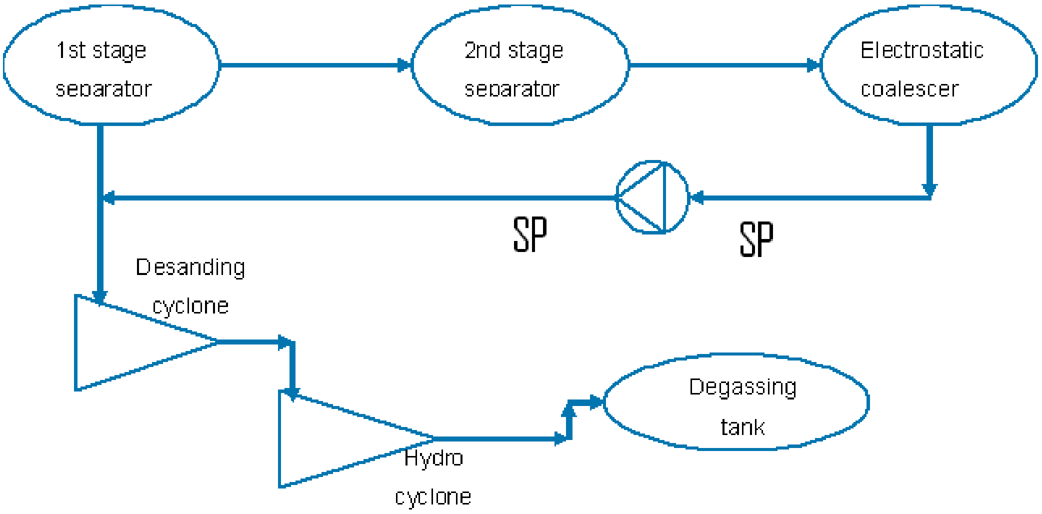


Figure 6-10: An overview of the separation train and the produced water treatment system, with a desander cyclone, a hydro cyclone, a degassing tank and a centrifugal pump boosting the produced water from the outlet of the electrostatic coalescer to the 1st stage separator outlet. SP = sample point.

The 1st stage separator was operated at 14 barg/ 55 °C, and the oil stream is heated before the 2nd stage separator which was operated at 2, 2 barg/ 71 °C and with a permanently closed produced water outlet. The electrostatic coalescer was operated at the same conditions, but with an open produced water outlet. Samples for droplet size measurements and oil in water concentration were taken upstream and downstream the booster pump, sample points are marked with SP. Parallel measurements were performed at all sampling points, two for concentration of oil and three for droplet size measurements, but only the mean values were available and are presented here.

The oil droplet size distributions upstream and downstream the pump, are shown in Figure 6.11, with the $D_{v,50}$ illustrated by a stapled horizontal line.

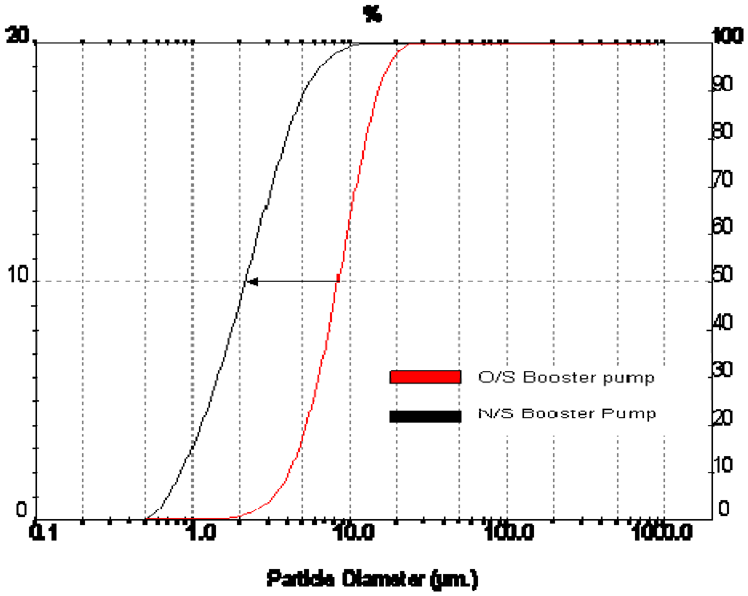


Figure 6-11: The oil droplet size distributions upstream and downstream the centrifugal pump in Case 1, red and black line respectively. The horizontal stapled line shows the $D_{v,\,50}$.

The droplet size measurements showed $D_{v,\,50}$ of ~8 µm upstream the pump and a $D_{v,\,50}$ of 2-3 µm downstream the pump. The oil concentration was measured to be 84 ppm.

6.2.2.1 Case 2

Case 2 is a gas condensate field. It has a process system with a separation train withstanding of three separation steps. The produced water treatment system is shown in Figure 6-12, with a desander cyclone, and a degassing tank. Water from the test separator is routed into the system upstream of the 2nd stage separator, which has a permanently closed produced water outlet. The water from the 3rd stage separator is pumped to the inlet of the degassing tank by a single stage centrifugal pump, from 1.1 barg to 6.5 barg. Samples for droplet size measurements and oil in water concentration were taken downstream the 3rd stage separator and downstream the booster pump, sample points are marked with SP. The analyst regarded that there was 10-20 meters from the sample point upstream the pump to the pump inlet, and 0.5 meter from the pump outlet to the downstream sampling point.

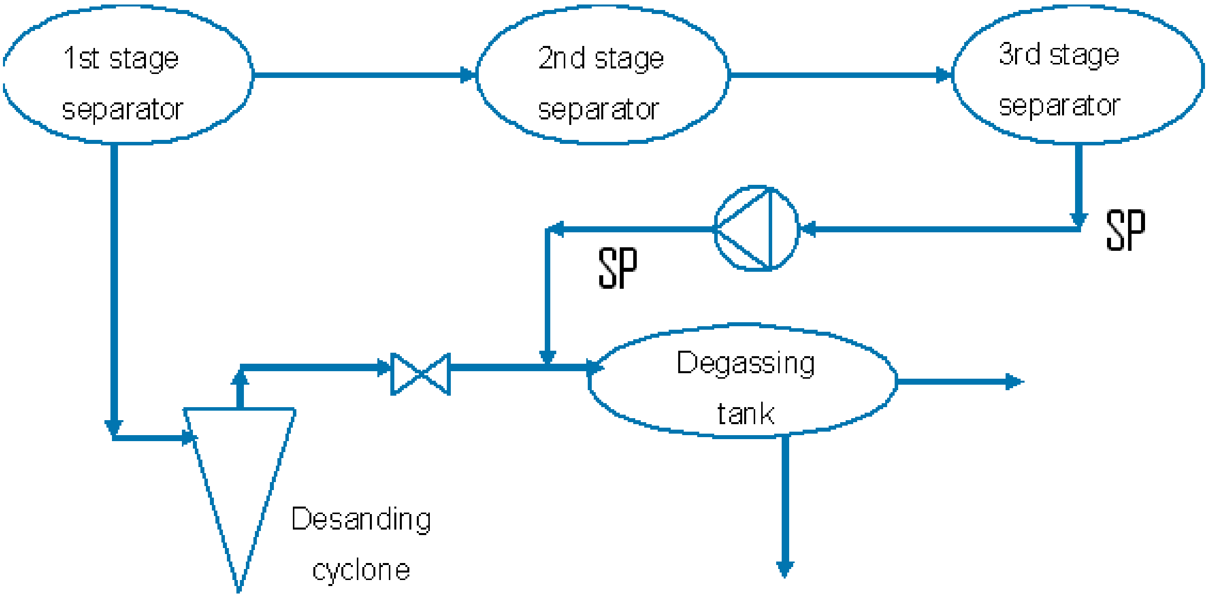


Figure 6-12: An overview of the separation train and the produced water treatment system, with a desanding cyclone, degassing tank and a centrifugal pump boosting the produced water from the 3rd stage separator to the inlet of the degassing tank. SP = sample point.

The droplet size measurements showed a $D_{v,\,50}$ of 3.8 µm both upstream and downstream the pump. The oil concentration was measured twice with 56 and 28 ppm as the respective results.

6.2.2.2 *Case 3*

The oil in Case 3 is a medium light crude oil (38 °API). Case 3 has a process system with a separation train withstanding of three separation steps. The 1st stage separator was operated at 11 barg, and the electrostatic coalescer was operated at 1.1 barg. The produced water treatment system is shown in Figure 6-13, with a hydro cyclone and a degassing tank. The water from the electrostatic coalescer outlet is pumped to the inlet of the hydro cyclone by a centrifugal pump from 1.1 barg to 11 barg. Samples for droplet size measurements and oil in water concentration were taken downstream the electrostatic coalescer and downstream the booster pump, sample points are marked SP.

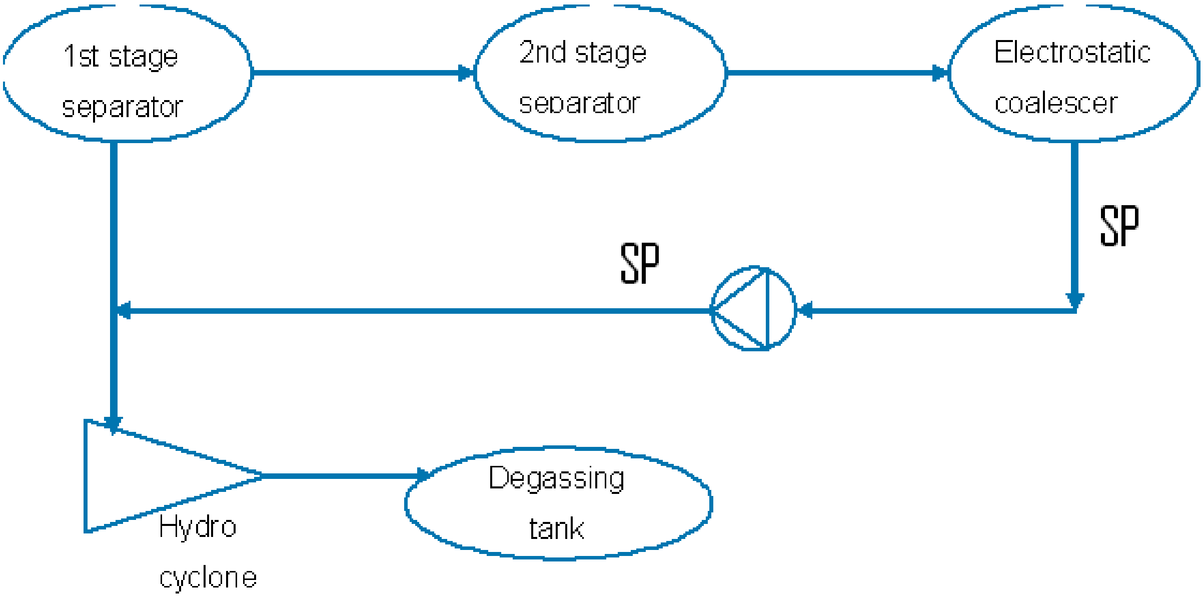


Figure 6-13:An overview of the separation train and the produced water treatment system, with a hydro cyclone, a degassing tank and a centrifugal pump boosting the produced water from the electrostatic coalescer to the 1st stage separator outlet. SP = sample point.

The droplet size measurements showed a $D_{v,\,50}$ of 4.6-4.7 µm upstream the pump and a $D_{v,\,50}$ of 2.9-3.5 µm downstream the pump. The oil concentration was measured to be 160 ppm.

6.2.2.3 Case 4

These test data was provided by CETCO which informed that this test was performed on a centrifugal pump boosting produced water for treatment in a hydro cyclone. The pump feed came from a produced water storage vessel containing water from the low pressure separator. CETCO regarded that the sampling points were located within two meters of the pump both upstream and downstream. No information regarding the pressures of the system was available.

$D_{V, 10}$, $D_{V, 50}$, $D_{V, 90}$ values were available, and are shown in Figure 6-14 displaying the effect of the centrifugal pump on the oil droplet distribution.

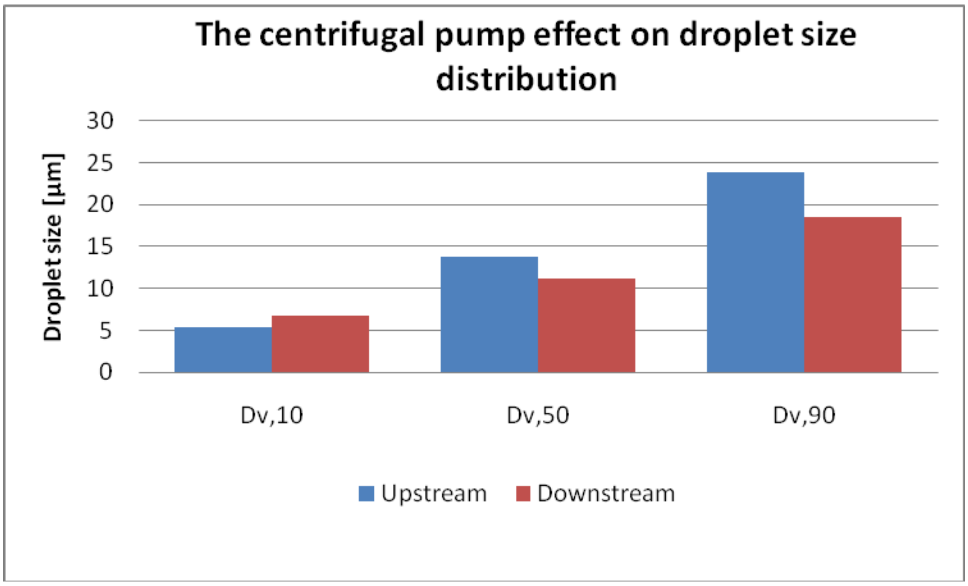


Figure 6-14: The effect of the centrifugal pump on the droplet size distribution, Case 4. This diagram is based on the data in Table 10-4, Appendix H.

$D_{V, 10}$, $D_{V, 50}$ and $D_{V, 90}$ values upstream the pump was 5.29 µm, 13.83 µm and 23.84 µm, while the downstream values was 6.68 µm, 11.25 µm and 18.52 µm. Figure 6-14 shows that the larger droplets decrease over the pump, while the smallest droplets increase.

6.2.3 Twin screw pumps

This section covers the test results available for the twin screw pumps. Two tests from the same field were available, and are denoted as Case 5a and Case 5b. Each case contained four pumps. The complete overview of the test data including operational data of the two cases is found in Appendix I.

6.2.3.1 Case 5

The oil in Case 5 is a heavy crude oil (~19° API). Case 5 has a process system with a separation train withstanding of three separation steps. First step withstands of 1st stage separator and a HP degasser in parallel. The oil is heated before a 2nd stage separator, and the 3rd step is two electrostatic coalescers in parallel. The produced water treatment system is shown in Figure 6.15, with the sample points marked SP. All steps have water outlets except for the HP degasser. Water from all these stages is pumped to the hydro cyclones by twin screw pumps for further treatment. Both the 1st and 2nd stage separator has two pumps in parallel, resulting in a total of 6 twin screw pumps in this system. From the hydro cyclones the water is routed to the degassing tank. Hydro cyclone reject is routed back to the inlet of the 2nd stage separator.

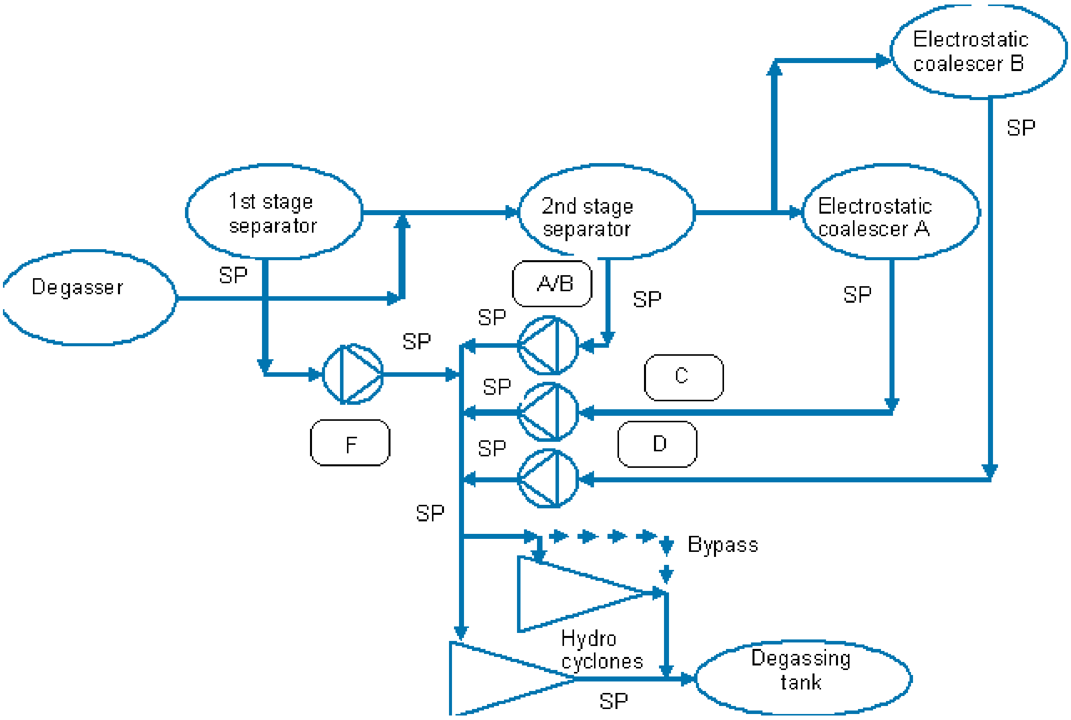


Figure 6-15: An overview of the separation train and the produced water treatment system in Cases 5a and 5b. Pumps F, A/B, C and D pump the produced water from the 1st stage separator, the 2nd stage separator and electrostatic coalescer A and B respectively. Sampling point= SP.

6.2.3.1.1 Case 5a

With regards to Case 5a only one hydro cyclone was in use, and some of the water was therefore routed around the hydro cyclone through a bypass. Samples for droplet size measurements and oil in water concentration were taken downstream the 1st and 2nd stage separators and both electrostatic coalescers (upstream the pumps), downstream their respective booster pumps and upstream and downstream the hydro cyclone. No information regarding the pressures of the system was available. An example of the droplet size distributions over the pumps, pump F is shown in Figure 6.16, and Figure 6-17 shows the droplet size distributions upstream and downstream all four pumps, represented by the $D_{v,50}$ values.

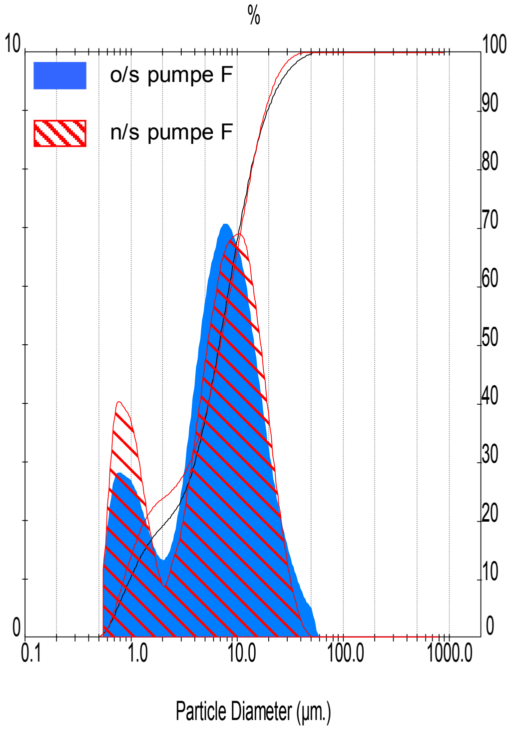


Figure 6-16: The droplet size distributions of pump F, with the volume % versus the particle diameter. The upstream distribution is given in blue and the downstream distribution in red.

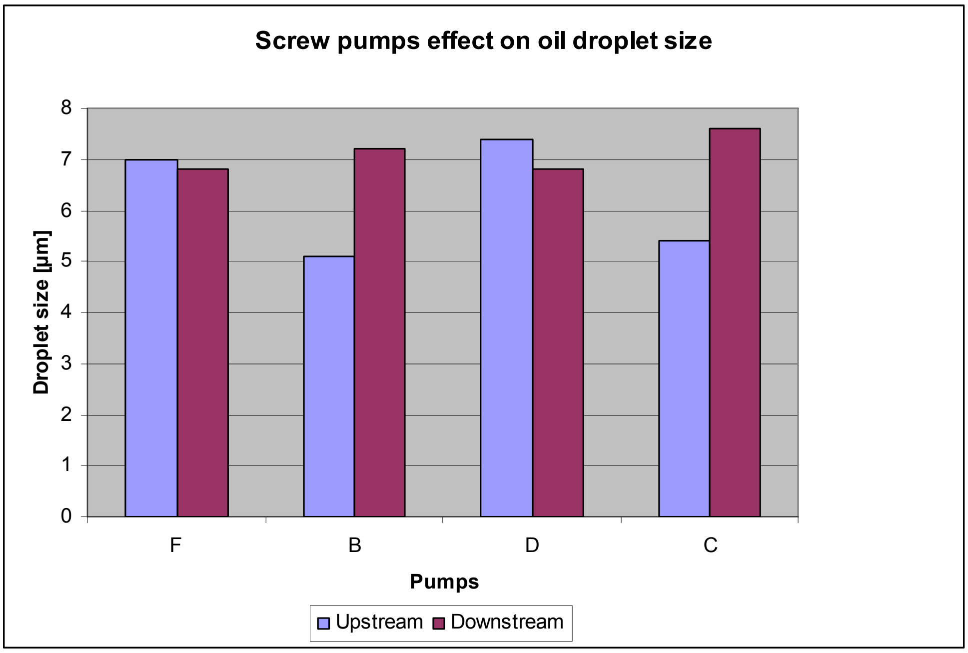


Figure 6-17: Diagram of the oil droplet sizes ($D_{v,\,50}$) upstream (blue) and downstream (purple) the pumps in Case 5a. The figure is made from data in Table 10-5, Appendix I.

Figure 6-16 shows that there's little change in the droplet size distribution curves for pump F. Figure 6-17 indicate that pumps F and D decrease the droplets from droplet sizes 7 µm and 7.4 µm upstream to 6.8 µm and 6.8 µm downstream the pumps, while pumps B and C increase the droplet sizes from 5.1 µm and 5.4 µm upstream and 7.2 µm and 7.6 µm downstream the pumps.

Samples taken upstream the hydro cyclone downstream the pumps show that $D_{v,\,50}$ increases from ~ 5-7 µm downstream the pumps to 11 µm upstream the hydro cyclone. This increase in droplet size indicates pipe coalescence, which is positive for the separation in the hydro cyclone. The hydro cyclone reduced the oil concentration from 158 ppm to 27 ppm.

6.2.3.1.2 Case 5b

In Case 5b pump F, D and C were tested again along with pump A which is installed in parallel to pump B. Both hydro cyclones were in operation during the test period. Samples for droplet size measurements and oil in water concentration were taken downstream the 1st and 2nd stage separators and both electrostatic coalescers, downstream their respective booster pumps and upstream the hydro cyclones. The analyst informed that there are 20-30 meters between the upstream sample points and the pumps, while the downstream sample points were directly on the pumps outlets. The inlet and outlet pressures of the pumps, along with the differential pressure, are given in Table 6-1.

Table 6-1: Overview of the inlet, outlet and differential pressures of the four pumps in Case 5b.

Produced water source	**Pump**	**Inlet pressure**	**Outlet pressure**	**ΔP**
		[barg]	[barg]	
1st stage separator	F	7,9	11,87	3,97
2nd stage separator	A	3,3	12,14	8,84
El. Coalescer B	D	3,1	12,13	9,03
El. Coalescer A	C	3,1	12,08	8,98

Figure 6-18 shows the droplet size distributions upstream and downstream all four pumps, represented by the $D_{v,10}$ and the $D_{v,50}$ values, the smallest and the larger droplets respectively.

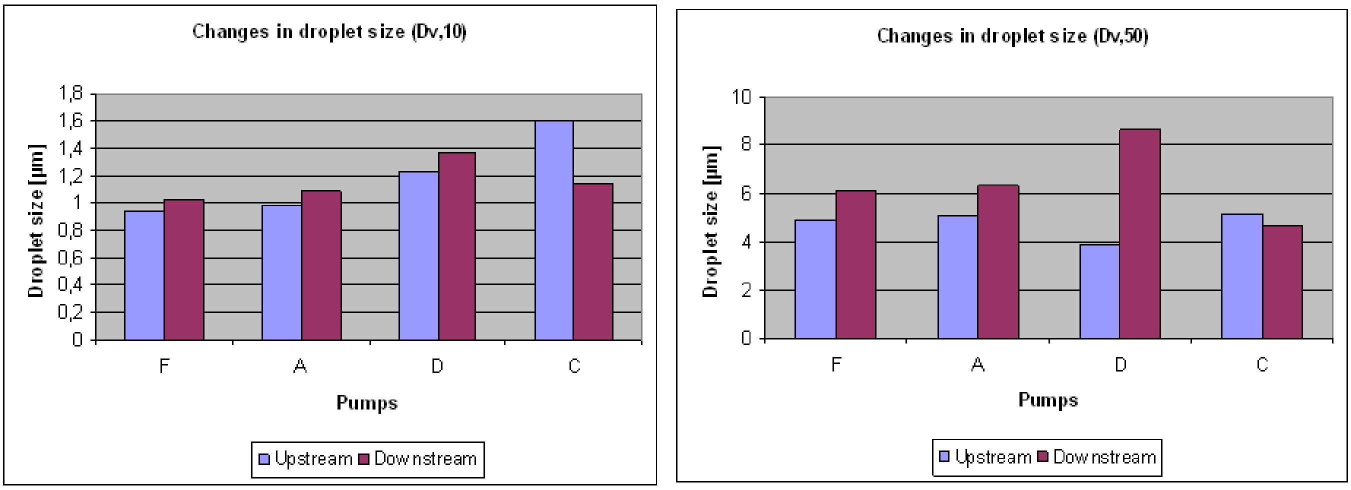


Figure 6-18: Diagram of the oil droplet sizes upstream (blue) and downstream (purple) the pumps in Case 5b. The $D_{v,\ 10}$ values are shown in the left diagram and the $D_{v,\ 50}$ values are shown in the right diagram. The figure is made from data in Table 10-6, Appendix I.

Figure 6.18 shows that the $D_{v,\ 10}$ and $D_{v,\ 50}$ values have the same development across the pumps. The droplet sizes ($D_{v,\ 50}$) for pumps F, A, D and C were respectively 4.95 µm, 5.06 µm, 3.9 µm and 5.15 µm upstream the pumps and 6.15 mm, 6.35 µm, 8.68 µm and 4.6 µm downstream the pumps. The figure indicates an increase in droplet size with pumps F, A and D, from while the oil droplets decrease in size with pump C.

When performing these tests complete droplet size distribution curves are generated by the analyzing equipment. The droplet size distributions upstream and downstream the pumps are combined for each pump, and shown for pumps F, A, D and C in Figure 6.19, 6.20, 6.21 and 6.22 respectively.

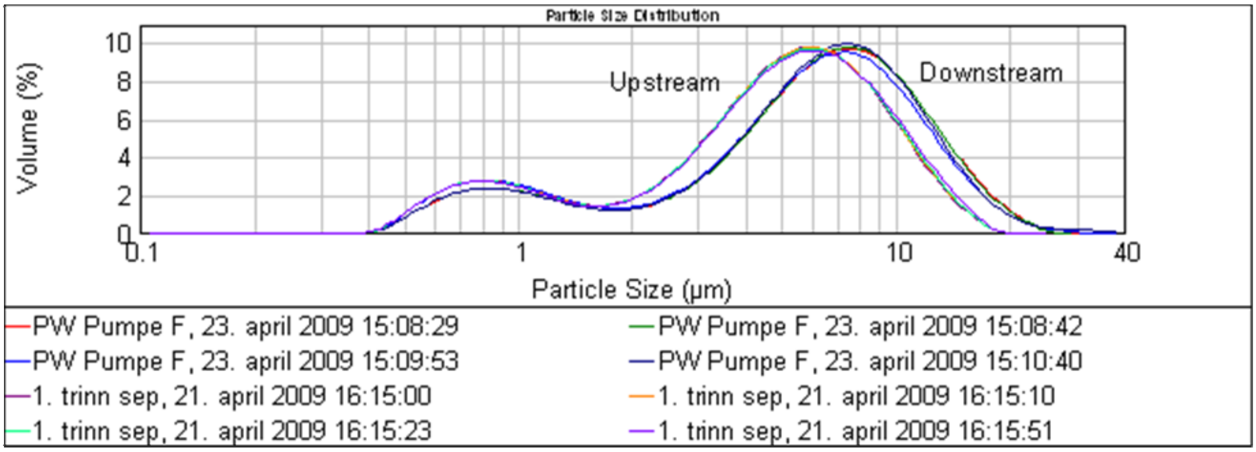


Figure 6-19: The droplet size distributions upstream (noted 1. trinn sep.) and downstream (noted PW Pumpe F) pump F, Case 5b. The X- axis gives the particle size in µm and the Y- axis gives the volume of the different particle sizes in %.

Figure 6.19 shows an increase in the amount of the largest droplets (> 6.5 µm) and a reduction of the smallest droplets (1-6.5 µm), with the curve moving to the right.

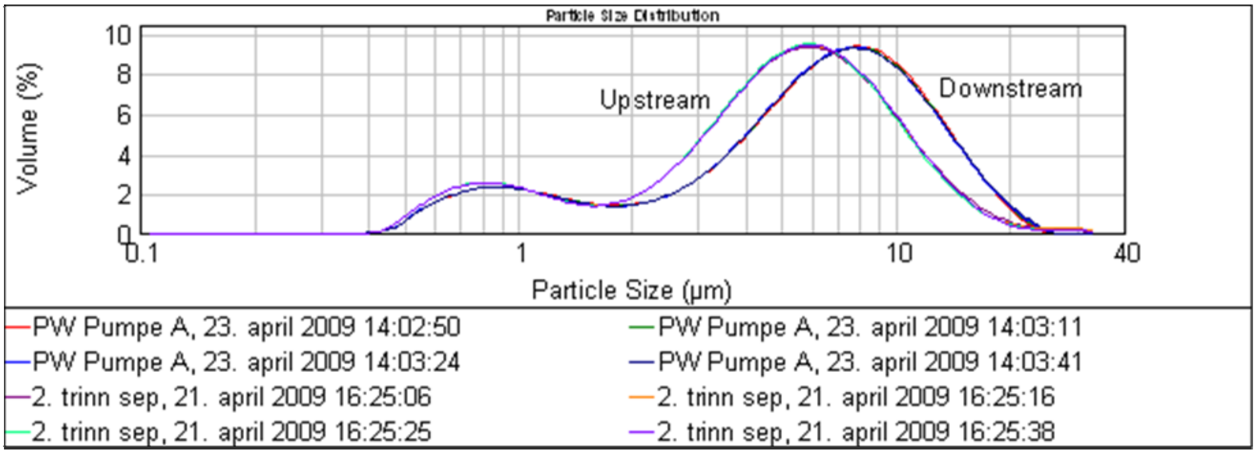


Figure 6-20: The droplet size distributions upstream (noted 2. trinn sep.) and downstream (noted PW Pumpe A) pump A, Case 5b. The X- axis gives the particle size in µm and the Y- axis gives the volume of the different particle sizes in %.

Figure 6.20 giving the curves for pump A shows that the amount of droplets larger than ~7 µm increases while the smaller droplets decreases.

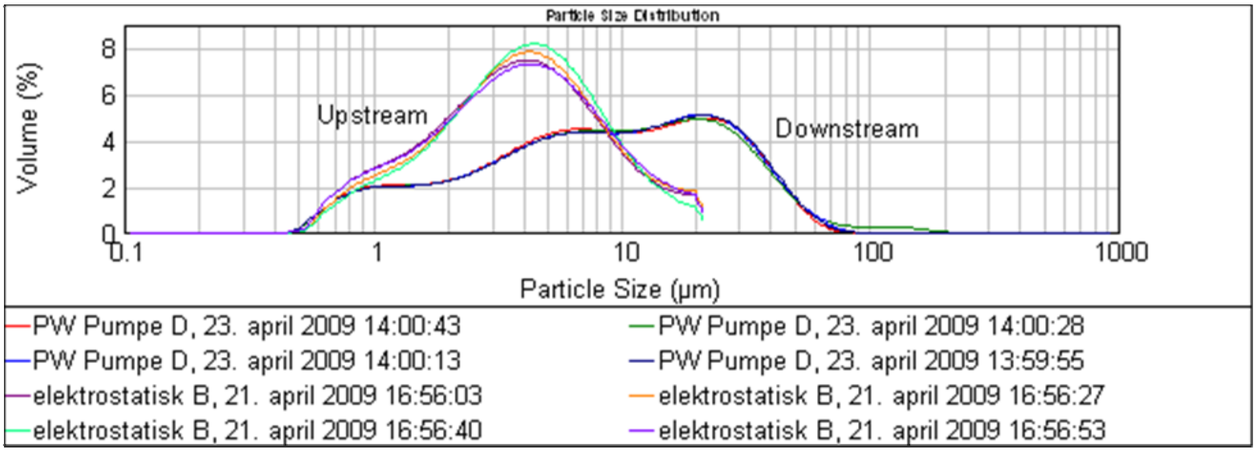


Figure 6-21: The droplet size distributions upstream (noted elektrostatisk B.) and downstream (noted PW Pumpe D) pump D, Case 5b. The X- axis gives the particle size in µm and the Y- axis gives the volume of the different particle sizes in %.

Figure 6.21 showing the curve for pump D shows large variance in the parallel measurements, especially with the samples taken upstream the pump. It shows an increase in the amount of larger droplet sizes and a decrease in the smaller droplets (< ~9 µm).

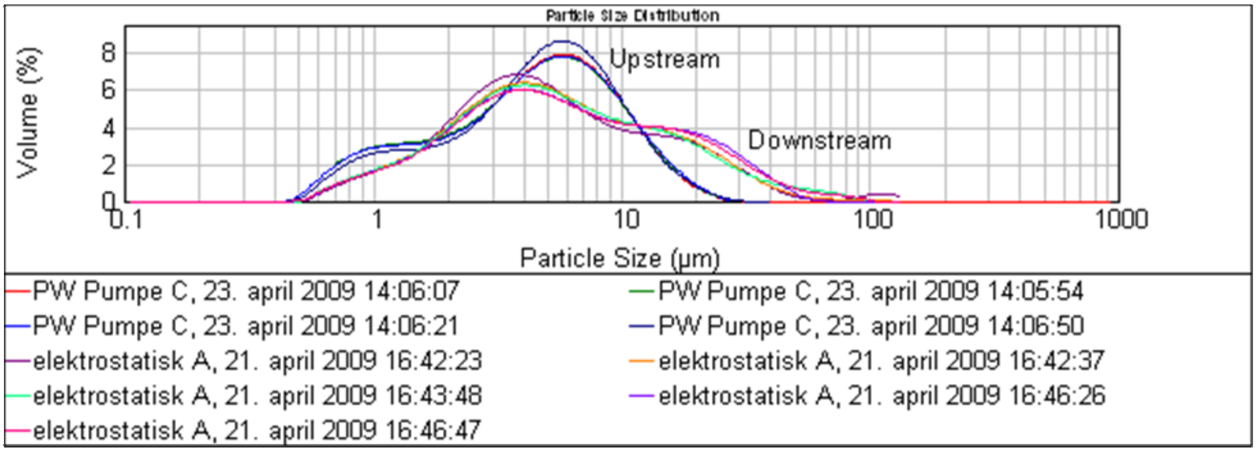


Figure 6-22: The droplet size distributions upstream (noted elektrostatisk A.) and downstream (noted PW Pumpe C) pump C, Case 5b. The X- axis gives the particle size in µm and the Y- axis gives the volume of the different particle sizes in %.

Figure 6.22 showing the curve for pump C shows large variance between the parallel measurements with both curves. It shows a small increase in the smallest droplets (~1 µm), a decrease in the amount of 2-3 µm droplets, and an increase in droplets ranging from 4 µm to ~10 µm. Droplet sizes > 10 µm show a significant decrease.

The droplet size at the inlet of the hydro cyclone is important. The samples were taken from the flow at the HC inlet containing droplets from all the pumps. Figure 6-23 shows the droplet sizes downstream the pumps, calculated for the total flow, and the droplet sizes measured upstream the hydro cyclones.

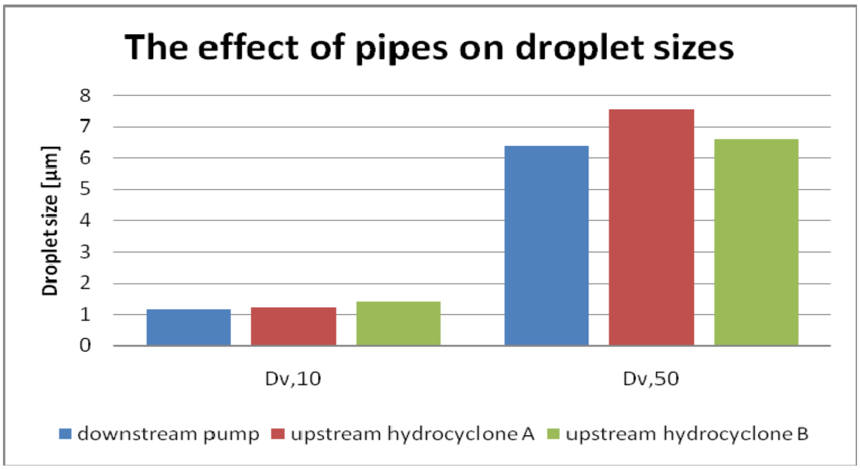


Figure 6-23: The effect of pipe flow on droplet sizes, with the droplet sizes ($D_{v,\ 10}$ and $D_{v,\ 50}$) downstream the pumps (calculated for the total flow, blue) and the droplet sizes measured upstream the hydro cyclones A and B (red and green). This figure is made from data in Table 10-7, Appendix I.

Figure 6-23 indicates that all droplet sizes (both the $D_{v,\ 10}$ and $D_{v,\ 50}$) have a certain increase in the pipe routing the flow to the hydro cyclones.

Hydro cyclone A show an efficiency of 68 % and a downstream droplet size of 3.8 µm, while hydro cyclone B show an efficiency of 58 % and a downstream droplet size of 4 µm.

6.3 Discussion

6.3.1 Literature survey

Bjørges ranking of pumps for boosting produced water is in many ways supported by other suppliers and by experiments. Bjørge, Per Gjerdrum AS and Seepex agree that the eccentric screw pump is the best choice with regards to droplet break-up, and are supported by the work of Flanigan et al (1988) and Environment & Research Technology (ERT) (1996). Axflow stated that the arc lobe pump is just as good. Flanigan ranked the lobe pump (further classification not known) as number two, while ERT found the lobe pump (further classification not known) to be suitable for some feed conditions. Bjørge rated the twin screw pumps as second best, piston pumps (reciprocating or rotating) as third and centrifugal pumps as the worse of these four pump types. Per Gjerdrum AS stated that the reciprocating piston pumps never have been viewed as low shear pumps. Flanigan rates the centrifugal pump at fourth place as well, but has the twin screw pump on fifth place, below the centrifugal pump. Shell's experience also indicates that properly designed and operated centrifugal pumps are better than the twin screw pumps in limiting break-up of droplets.

Flanigan et al (1992) proved that eccentric screw pumps at a differential head of 12 bars broke up droplets > 16 μm and increased smaller droplets (< 16 μm). The downstream hydro cyclone removed oil with 90 % efficiency. Another test, performed offshore on a large eccentric screw pump with inlet sizes 11 to 17 μm, proved that the inlet/outlet ratio was 0.95 of all differential heads (4-7.65 bars) and Flanigan et al. stated that this could be viewed as no significant break-up.

Centrifugal pumps are defended by Ditria and Hoyack (1994) in cases of properly sizing and operation, which is supported by ERT (1996) that proved that centrifugal pumps can eliminate shearing when they are properly operated with good efficiency. Schubert (1992) referred to tests for optimal design of centrifugal pumps showing an outlet/inlet ratio of 0.75-0.80, indicating droplet break-up. ERT showed that a multi stage centrifugal pump is better than a single stage pump.

6.3.2 Offshore experiments - Centrifugal pumps

One element of uncertainty that is relevant for all four cases is the effect of pipe coalescence. As some distance from the sampling points to the inlets of the pumps, and in some cases from the pumps to the sampling points downstream the pumps, is known or assumed there could be some uncertainty with regards to the actual droplet sizes at the pumps inlets. Also, bends and restrictions in the pipes that could create shearing of droplets have not been evaluated here.

Looking at Case 1 the decrease in droplet size ($D_{v,\,50}$) from 8 μm to 2-3 μm across the pump is an indication of droplet break-up. The droplet size upstream of the pump is of a size range that is more subjected to shear. At the same time, an oil concentration of 84 ppm may cause reduced coalescence. Both of these factors should favor droplet break-up and may contribute to explaining the high degree of droplet shearing.

Case 2 shows a constant droplet size ($D_{v,\,50}$) of 3.8 μm indicating that the pump has no effect on the droplet size. The droplet size upstream of the pump is of a size range that is less subjected to shear and could be too small to break-up, favoring coalescence. On the other hand the oil concentration of 56 or 28 ppm can cause reduced coalescence, favoring droplet break-up. The testing referred to in Case 2 gave approximately the same droplet sizes throughout the whole system. This creates uncertainty with regards to the effect of the pump, but can also support that the droplets are too small to be affected by shear.

Case 3 indicates droplet break-up with a decrease in droplet size ($D_{v,\,50}$) from 4.6-4.7 μm to 2.9-3.5 μm across the pump. The droplet size upstream of the pump is fairly small in comparison with the tests of Flanigan et al. (1992) which used droplet sizes of 11-17 μm. This could favor coalescence, but the droplets are still dispersed further. The oil concentration was the highest of Cases 1, 2 and 3, with 160 ppm and should by theory be the case with the highest degree of coalescence.

Case 4 indicates coalescence of the smallest droplets with an increase from 5.29 μm to 6.68 μm ($D_{v,\,10}$), and droplet break-up of the larger droplets with a decrease from 13.83 to 11.25 μm ($D_{v,\,50}$). Case 4 shows higher droplet sizes upstream the pumps than the first three cases. This is assumed to be partly because the equipment used, Jorin, doesn’t measure the smallest droplets. Still, the $D_{v,\,50}$ values upstream of the pump is in the size range more subjected to shear and can contribute to explaining the droplet break-up.

Figure 6-24 illustrates the effect of all four centrifugal pumps allowing for a comparison.

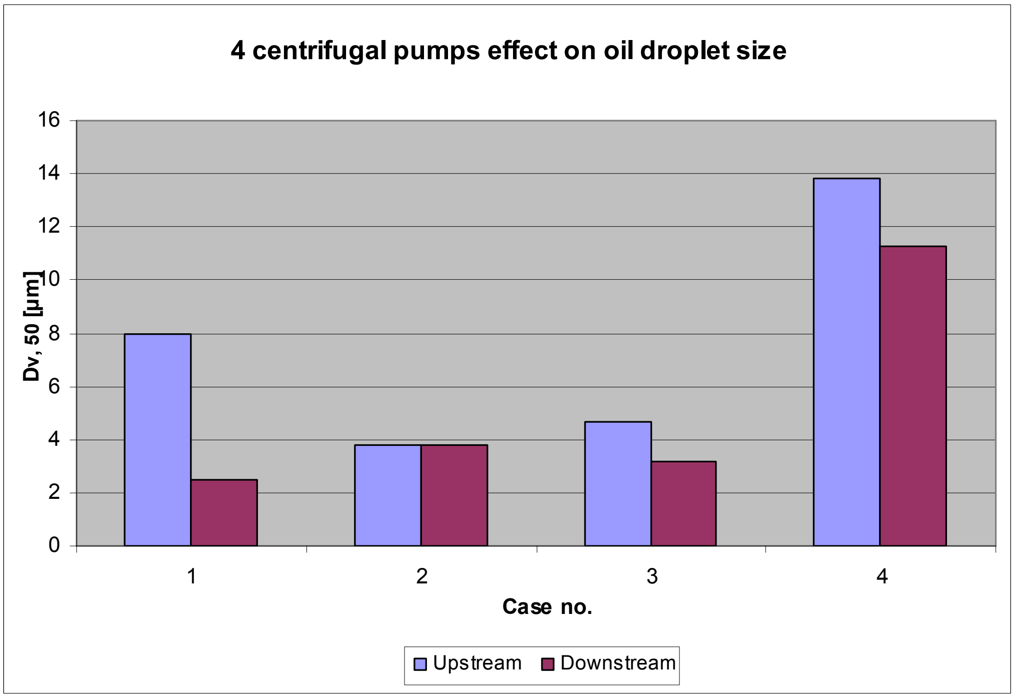


Figure 6-24: A comparison of the effect of the four centrifugal pumps on oil droplets, demonstrated by the volumetric mean diameter ($D_{v,\,50}$) upstream (blue) and downstream (purple) the pumps. The figure is made from data in Table 10-3, Appendix H.

Figure 6-24 indicates that the smaller droplets (Cases 2 and 3) experience no effect or a smaller degree of break-up, while the larger droplets (Cases 1 and 4) are more effectively dispersed.

The droplet sizes downstream the pumps in Cases 1 and 3 resemble each other, which could indicate a minimum droplet size that can be dispersed, referring to Equation 4-4 in Chapter 4.1.2. The smallest droplets of Case 4 ($D_{v,\,10}$) are assumed to be of a similar size as Cases 2 or 3 ($D_{v,\,50}$), taking into account the error resulting from Jorin’s measurement domain. These show a degree of coalescence, with droplet size ratio 1.26 across the pump.

The pumps (Cases 1, 2 and 3) have quite different differential pressures, and Figure 6-25 shows the oil droplet ratios as a function of the differential pressure. Case 4 is included in the figure although the differential pressure wasn't available.

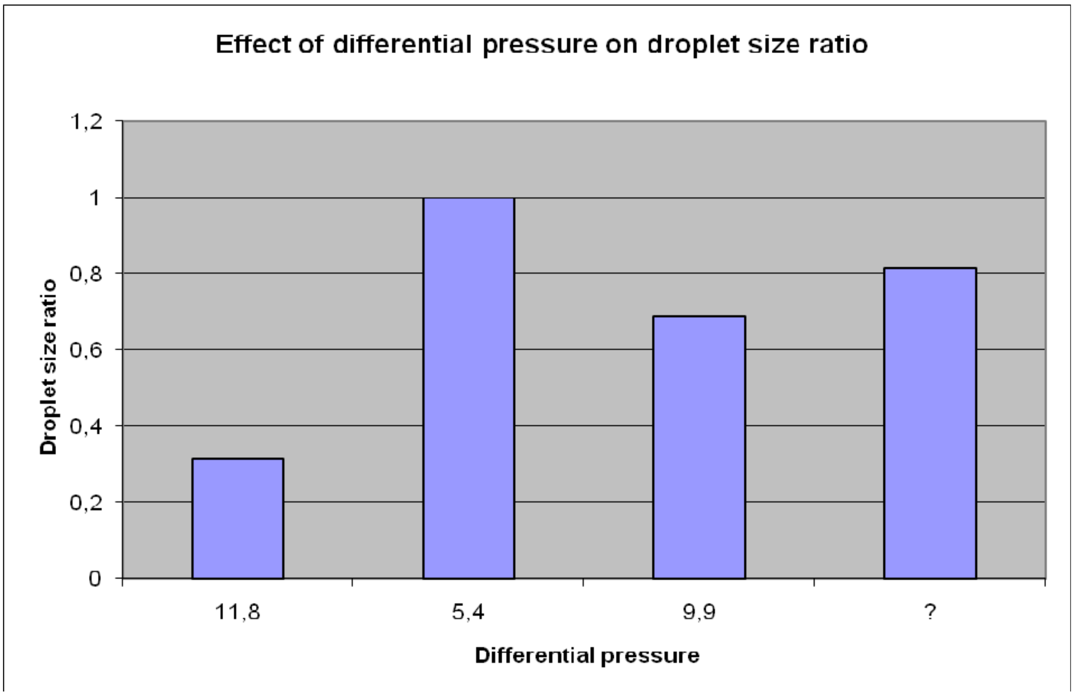


Figure 6-25: The droplet size ratios as a function of differential pressure of the pumps in Cases 1, 2, 3 and 4. The differential pressure for Case 4 wasn't available. From the left to the right pumps 1, 2, 3 and 4 are situated. The figure is made from data in Table 10-3, Appendix H.

Figure 6-25 shows that Case 1 has a smaller droplet size ratio than the other three cases, indicating that the pump of Case 1 creates higher shear forces than the other pumps. The process data sheets of the pumps show that the pumps in Cases 1 and 2 are same type single stage pump from the same supplier. The configurations of Case 3 and 4 are not known. The configuration and design of the pumps are believed to have had an impact on the effect the different pumps have shown on the oil droplets, with reference to the literature survey.

Figure 6-25 shows that the larger differential pressure, the larger is the degree of droplet break-up. Case 1 has twice the differential pressure of Case 2 (11.8 bar to 5.4 bar) and shows the largest decrease in droplet size, while Case 2 show no effect of the pump. Case 1 also has twice the droplet size upstream of the pump as Case 2, which could have had an impact on the result. Both the differential pressure and the degree of droplet break-up of Case 3 are between those of Cases 1 and 2. Case 4 shows a degree of droplet break-up in between Cases 2 and 3.

Focusing on the $D_{v,\ 50}$ values, none of the centrifugal pumps show coalescence of the oil droplets. Thus it may seem like the centrifugal pump is consistently shearing the droplets. The results from the centrifugal pumps indicate a trend where higher differential pressure and higher droplet sizes upstream of the pump give a higher degree of droplet break-up.

6.3.3 Offshore experiments – Twin screw pumps

Case 5 is a heavy crude oil, and therefore it is assumed that it has different properties than the lighter oils from Chapter 6.3.1.

Boosting water from different separators in the separator train, the four twin screw pumps are boosting water with different properties, with regards to oil concentration, load and so on. An example of this is the decrease in the viscosity of the oil caused by heating of the oil stream routed from 1^{st} to 2^{nd} stage separator. Also, water separated late in the system is known to be dirtier than the water separated in the 1^{st} stage separator. Ageing of the oil droplets becomes worse as well.

As with the centrifugal pumps the effect of pipe coalescence is a general element of uncertainty. In Case 5b the distances from the sampling points to the inlet of pumps were regarded to be 20-30 meters, while the sampling point downstream the pumps were directly on the outlet of the pumps. It's assumed the same sampling points were used in Case 5a. This creates some uncertainty with regards to the actual droplet sizes at the pumps inlets. Bends and restrictions in the pipes that could create shearing of droplets have not been evaluated here.

The four twin screw pumps in Case 5a indicate different effect on the droplet sizes ($D_{v,\ 50}$) as pump F and D indicate droplet break-up with droplet sizes of 7 µm and 7.4 µm upstream to 6.8 µm and 6.8 µm downstream the pumps, while B and C indicate coalescence with droplet sizes of 5.1 µm and 5.4 µm upstream and 7.2 µm and 7.6 µm downstream the pumps.

Pumps F and D show a small degree of droplet break-up with a droplet size ratio of ~0.97 and ~0.92. Referring to Flanigan et al. (1992) who viewed a ratio of 0.95 as no significant effect, pumps F and D can be viewed as having no significant effect on the oil droplets. Pumps B and C, on the other hand, show a droplet size ratio of ~1.4.

Pumps F and D show higher inlet droplet sizes than pumps B and C, ~7 µm versus ~5 µm. This could be a contributing factor to the different effect of the pumps, and correspond well with the theory of larger droplets favoring droplet break-up.

Although pumps D and C both pump water from electrostatic coalescers and have the same load and oil concentration, they appear to exhibit different effect on the oil droplets.

Pump F has an oil concentration of 360 ppm, the highest of the four pumps. This may have reduced the droplet break-up of the droplets.

These results indicate no trend with regards to load or oil concentration. As neither the differential pressure nor the rotational speed of the pumps was available, trends with regards to these factors can’t be evaluated.

The oil droplets seem to coalesce in the piping downstream the pumps, increasing the droplet size from ~7 µm downstream the pump to 11 µm upstream the hydro cyclone. This makes the flow more suitable for separation in the hydro cyclone, which reduced the oil concentration from 158 to 27 ppm.

In Case 5b $D_{v,\,10}$, $D_{v,\,50}$ and $D_{v,\,90}$ values were available along with the droplet size distribution curves. As the smallest droplets are most critical in the separation the focus was put on $D_{v,\,10}$ and $D_{v,\,50}$ with support of the droplet size distribution curves.

Figure 6-18 shows that the $D_{v,\,10}$ values follow the same development as the $D_{v,\,50}$ values. Pumps F, A and D indicate coalescence with the droplet sizes increasing from respectively 4.95 µm, 5.06 µm and 3.9 µm upstream to 6.15 µm, 6.35 µm and 8.68 µm downstream the pumps. Pump C indicates droplet break-up with the droplets size decreasing from 5.15 µm upstream to 4.6 µm downstream the pump.

Figure 6.22, presenting the upstream distribution curve of pump C shows that it exhibits a different shape than the curves of the other pumps, giving higher D_v values. The downstream distribution of pump D in Figure 6-21 shows a similar shape. These irregularities, which are assumed by Mator (Heitmann 2009b) to be caused by solid particles that have interfered with the measurements, make it difficult to compare all four figures directly. As in Case 5a, pumps D and C were assumed to have similar effect on the oil droplets, with regards to fluid properties and operational factors. The irregularities from the measurements on pump C creates an uncertainty with regards to the droplet sizes measured at this pump.

Although the larger degree of coalescence shown by pump D is assumed to be caused by solid particles, it is reasonable to believe that a certain degree of coalescence has happened. This is because the ratio of the $D_{v,\ 10}$ values (1.11) is similar to those of the $D_{v,\ 10}$ values of pumps F and A (1.09 and 1.1), referring to Figure 6-18.

Pump D has an oil concentration of 49 ppm, which may cause reduced coalescence and favor droplet break-up. It also has the smallest load and a speed of 461 rpm, which should favor coalescence. All the pumps show droplets in the size range which is less subjected to shear upstream the pumps ($\leq 5\ \mu$m), which theoretically should favor coalescence.

As shown in Table 10-6 in Appendix I, the pumps are operated at different pressures, loads and rotational speeds. Figure 6-26 illustrates the effect of the differential pressures in Case 5b, demonstrated by the droplet size ratios.

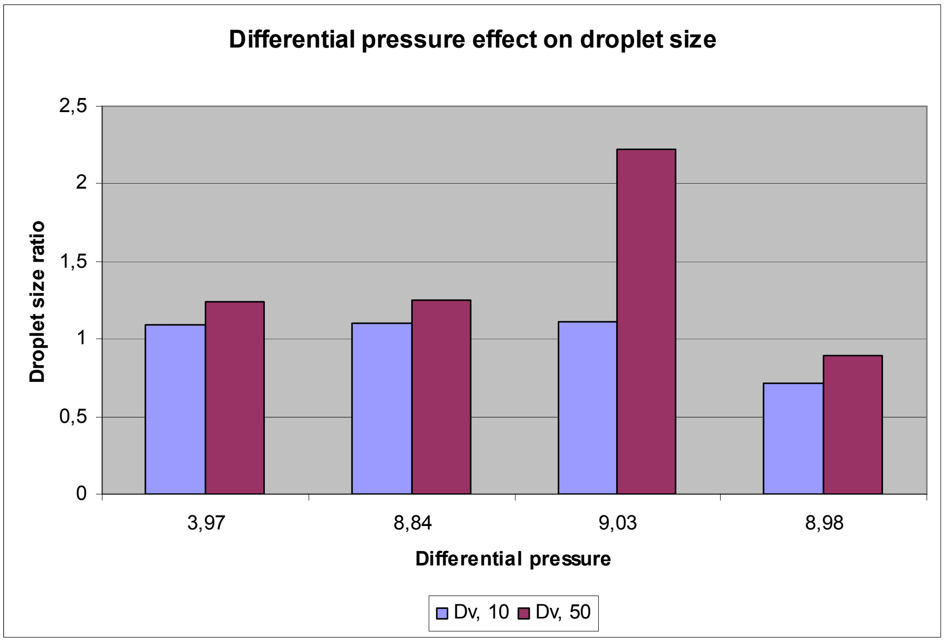


Figure 6-26: The droplet size ratios for both $D_{v,\ 10}$ (blue) and $D_{v,\ 50}$ (purple) as a function of the differential pressure of the pumps in Case 5b. From the left to the right pumps F, A, D and C are situated. This figure is made from data in Table 10-8, Appendix I.

Figure 6-26 shows that pumps F and A, with differential pressures of 3.97 bars and 8.84 bars respectively, have approximately the same droplet size ratio. Figure 6-18 shows that the droplet sizes upstream and downstream these pumps are similar as well. Pumps A, D and C having approximately the same differential pressures (~9 bars) and inlet pressures, show different droplet size ratios. Pump C is the only one showing a droplet size ratio below 1.

These differences make it reasonable to assume that the differential pressure doesn't dominate the pumps effect in this case.

Looking closer at pumps F and A, pump A is also operated with twice the rotational speed of pump F (809 to 379 rpm). On the other hand pump F have twice the suction pressure of pump A, and 50 % higher oil concentration. These factors may have had an effect on the droplet sizes.

With reference to Figure 6-23 no significant increase is seen in the piping routing the flow from the pumps to the hydro cyclones. The droplet sizes in the hydro cyclone feeds are ~ 7.5 µm and ~ 6.6 µm ($D_{v,\,50}$). The hydro cyclones A and B show efficiencies of respectively 68 % and 58 %, and downstream droplet sizes of 3.8 and 4 µm. The test report showed that the hydro cyclones were not operated optimally with respect to flow rates and differential pressures. Even with feeds with droplet sizes below 10 µm and with insufficient differential pressure, the hydro cyclones removed oil with efficiencies of 60-70 %. Operated with the correct differential pressure, the same hydro cyclones showed higher efficiencies (>80 %).

Comparing the centrifugal pumps and the twin screw pumps is challenging as there are variations in the amount of operational data available. The droplet size ratios of the different pumps can though be compared, such as in Figure 6-27.

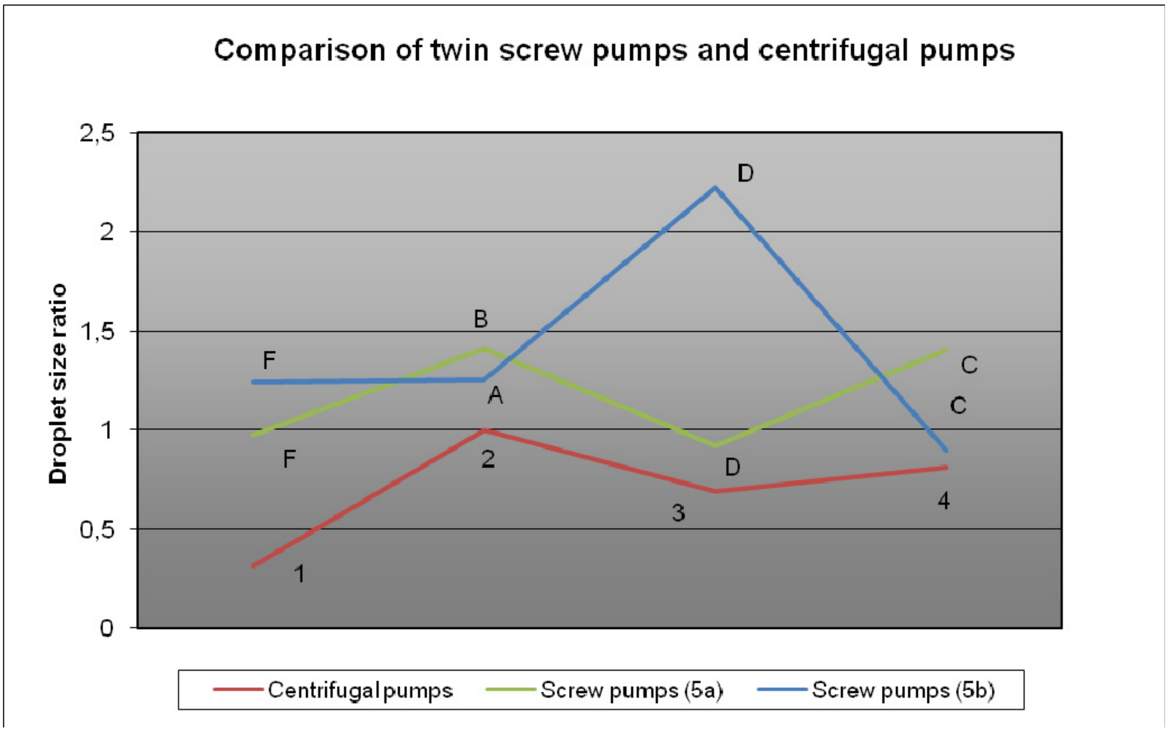


Figure 6-27: A comparison of the droplet size ratios ($D_{v,\,50}$) of the twin screw pumps (green=5a, blue=5b) and the centrifugal pumps (red). A droplet size ratio > 1 indicates coalescence and < 1 indicates droplet break-up. This figure is made from data in Table 10-9, Appendix J.

Figure 6-27 shows that there are variations of the effect of the pumps of the same pump type. Looking at the curves for Cases 5a and 5b, only the pumps downstream the 2nd stage separator, pumps A (5b) and B (5a) indicate coalescence in both cases. These pumps show similar droplet sizes in both 5a and 5b with droplet size ratios of ~1.4 and 1.25. Both pumps F and D show larger droplet sizes upstream the pumps in Case 5a, where they indicate no significant effect, than in Case 5b where they indicate coalescence with droplet size ratios of ~1.24 and ~2.22. Pump C shows the same droplet size upstream the pump in both cases, but indicates droplet break-up in 5a and coalescence in 5b, with droplet size ratios of ~1.4 and ~0.9. As Case 5 covers four flows with relative small oil droplet sizes, the effect of the twin screw pumps on larger droplets should be looked into. The comparison of Case 5a and 5b could indicate that the twin screw pump will break up larger droplets.

Figure 6-27 also shows that while the twin screw pumps indicate a degree of coalescence at some of the pumps, the centrifugal pumps consistently indicate droplet break-up or a constant droplet size. These results indicate that the twin screw pumps are gentler to the oil droplets and should be more applicable in the produced water treatment system with regards to shearing.

These results are the opposite of what Flanigan et al. found, as they stated that the centrifugal pump is better than the twin screw pump. It is emphasized that the detail design of the pumps is believed to impact the effect on oil droplets. The results do however support the ranking by Bjørge. While Shells guideline states that 3.45 bars boosting per stage is the best design of a centrifugal pump, Ditria and Hoyack stated that a single stage centrifugal pump operated at maximum differential pressure of 5.5 bars will cause minimum break-up. The two pumps known to be single stage centrifugal pumps are operated at differential pressures of 11.8 and 5.4 bars, where the latter indicates no break-up, corresponding well with Ditria and Hoyack.

6.4 Recommendations for further work

The pump types and pump designs that are commonly used in produced water systems today, and pumps being developed for this application should be further looked into with regards to the effect on oil droplet break-up and coalescence. This thesis gives an overview of work that has been performed upon today and the results from this work. The offshore tests referred to have not been performed with the intention to look into the effect of pumps and therefore attain uncertainties and sources of errors.

Specific designed tests, similar to that of ERT (1996) should be performed on new pumps where the focus is low shear and application in the produced water treatment system. The author has understood from the suppliers that there has been and still is an on-going development of the pump types delivered for this purpose. Such a test should be performed within a lab to make it possible to change operational conditions and rule out as many uncertainties as possible.

7 Desanding cyclones

In this chapter the information regarding desanding cyclones, acquired during the literature survey, contacts with the suppliers and the reports from the offshore tests, are presented. The chapter ends with a discussion of the presented results, and a recommendation of further work.

7.1 Literature survey

Several suppliers of desanding cyclones to produced water treatment systems were contacted regarding their experience with shear and coalescence of oil droplets within the desanding cyclone.

Merpro Ltd stated that they have witnessed a degree of coalescence in the desanding cyclones. However, over their desanding cyclones, they have not performed any specific droplet size or oil in water concentration measurements.

Cyclotech stated that they have not performed oil droplet size measurements on their desanding cyclones.

Mozley and **Natco Norway** (former ConSept) are today both part of the **Natco Group**, where Mozley covers the desanding cyclones.
Natco Norway have not performed tests with regards to desanding cyclones and droplet sizes.
Mozley have not performed any droplet size measurements regarding the desanding cyclone, but regards that they have some knowledge from a system upgrade on a BP platform in the mid 90's. Included in this upgrade were adding Mozley desanders and Vortoil deoilers as well as a flash drum. A Mozley report (1999) states that an improved performance of the deoiler was measured when the desander was in operation, and that BP concluded that oil droplets coalesced in the desander.
BP questions this conclusion, and states that in general it is more likely that the reason for the enhanced performance of the deoilers was caused by the fact that the desanding cyclone removed the solids that otherwise clogged the liners in the deoiler.

FLSmidth (former Krebs Engineering) have performed some tests regarding the effect of their desanding cyclones on oil droplets. A paper was produced, but this wasn't available by the end of this thesis. Some of the results are referred to by Lohne (1994).
He reported from testing of Krebs 2" and 4" desanding cyclones executed at the Orkney Water Test Centre on behalf of Krebs Engineers. It was found that shearing of oil droplets through the desanding cyclone only took place at very high flow rates (> 100 % nominal) and only at large droplet size (> 35 µm). Lohne reported that at some, not specified, test conditions a limited degree of coalescence was observed. The conclusion made from these tests was that the desanding cyclone was unlikely to damage the oil removal performance of the downstream hydro cyclone, hence would not break up the oil droplets.

Rawlins and Hewett (2007) referred to a well head desanding cyclone application where the cyclone was placed down hole directly on the outlet of a sucker rod pump producing 28-30° API oil. An increase in the oil-water separation performance in the downstream separator was experienced and the authors stated that this could indicate oil droplet coalescence in the well head desanding cyclone.

7.2 *Offshore experiments*

Internal reports from offshore tests related to troubleshooting and optimization of the process system and the produced water treatment system at offshore platforms, have supplied this thesis with test data from real conditions. The different tests are denoted Case X (X=1, 2...). The numbers are connected to those of the pumps. Case 6 was performed and documented by Aquateam. Mator AS has performed all the other tests and written the following reports. The data available for desanding cyclones are presented and evaluated in the following chapters. An overview of the test data including operational data is found in Appendix K.

7.2.1 Case 1

Case 1 has a process system with a separation train withstanding of three separation steps. The produced water system is shown in Figure 7-1, with a desanding cyclone, a hydro cyclone, and a degassing tank. The desanding cyclone size is 3”.

Samples for droplet size measurements and oil in water concentration were taken downstream the booster pump, downstream the 1st stage separator and downstream the desanding cyclone. Parallel measurements were performed at all sampling points, two for concentration of oil and three for droplet size measurements. The average values are presented here.

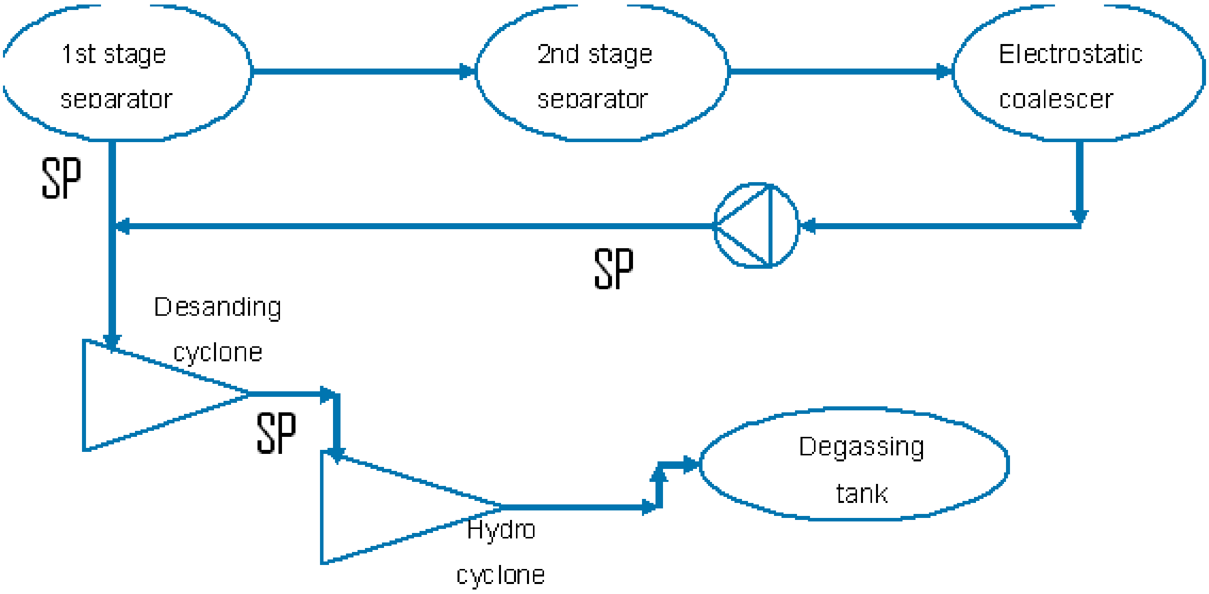


Figure 7-1: An overview of the separation train and the produced water treatment system in Case 1, with a desander cyclone, a hydro cyclone, a degassing tank and a centrifugal pump boosting the produced water from the outlet of the electrostatic coalescer to the 1st stage separator outlet. SP = sample point.

The inlet flow of the desanding cyclone is a mixture of produced water from the 1st stage separator and the electrostatic coalescer. The oil droplets in the water from the electrostatic coalescer have a $D_{v,\,50}$ of 2-3 μm, while the droplets in the water from the 1st stage separator have a $D_{v,\,50}$ of 4.3 μm. The samples taken downstream the desanding cyclone show a $D_{v,\,50}$ of 8.9 μm. The concentration of oil in the water decreases from approximately 80-110 ppm to 70 ppm over the desanding cyclone.

7.2.2 Case 2

Case 2 has a process system with a separation train withstanding of three separation steps. The produced water system is shown in Figure 7-2, with a desander cyclone, and a degassing tank. The desanding cyclone size is 3”.

Samples for droplet size measurements and oil in water concentration were taken downstream the 1st stage separator and downstream the desanding cyclone. The analyst regarded the distance between the sample points downstream the separator and upstream the desanding cyclone to be approximately 4-5 meters. The desanding cyclone had four outlets and the sample point was located after the gathering of three of the four outlets of the desanding cyclone.

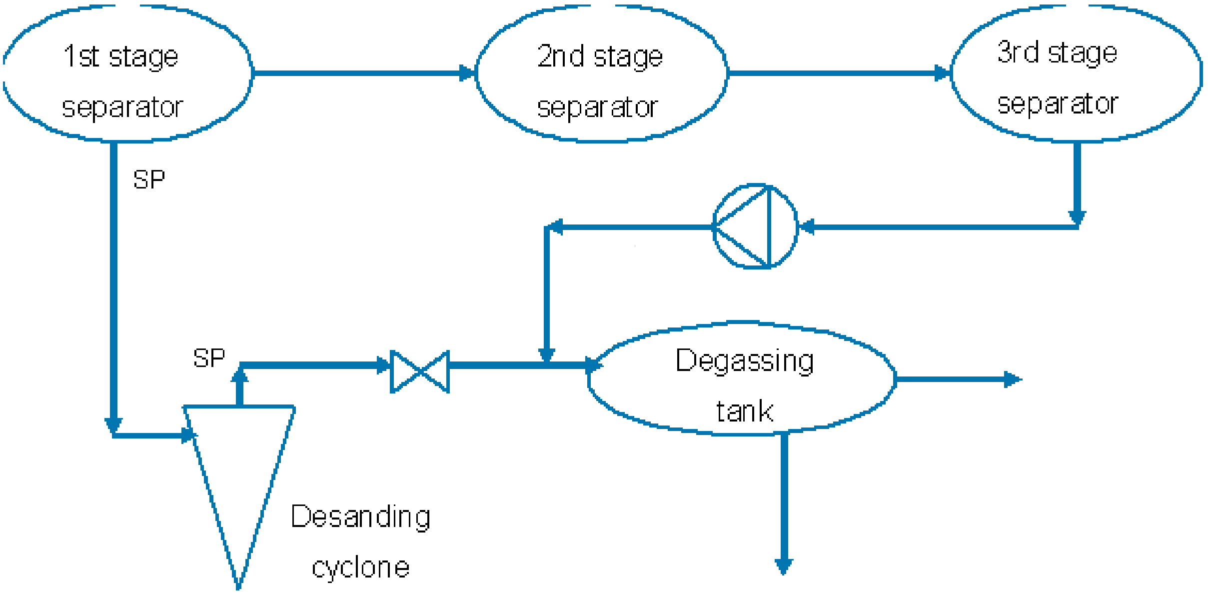


Figure 7-2: An overview of the separation train and the produced water treatment system in Case 2, with a desanding cyclone, degassing tank and a centrifugal pump boosting the produced water from the 3rd stage separator to the inlet of the degassing tank. SP = sample point.

The oil droplets upstream the desanding cyclone show a $D_{v,\ 50}$ of 4.2 µm, while the oil droplets downstream the desanding cyclone show a $D_{v,\ 50}$ of 3.8 µm. The oil concentrations were measured to being 52 and 127 ppm upstream and 78 ppm[1] downstream the desanding cyclone.

7.2.3 Case 6

Case 6 has a produced water injection system that re-injects the produced water after it has been treated in the produced water treatment system. Produced water from the 1st stage separator goes through a hydro cyclone and to a degassing tank, before entering a desanding cyclone and further treatment prior to re-injection, as shown in Figure 7-3. The size of the desanding cyclone is ~4”. Samples for droplet size measurements and oil in water concentration were taken downstream the degassing tank and downstream the desanding cyclone and are marked SP in Figure 7-3. The produced water temperature was approximately 70 °C.

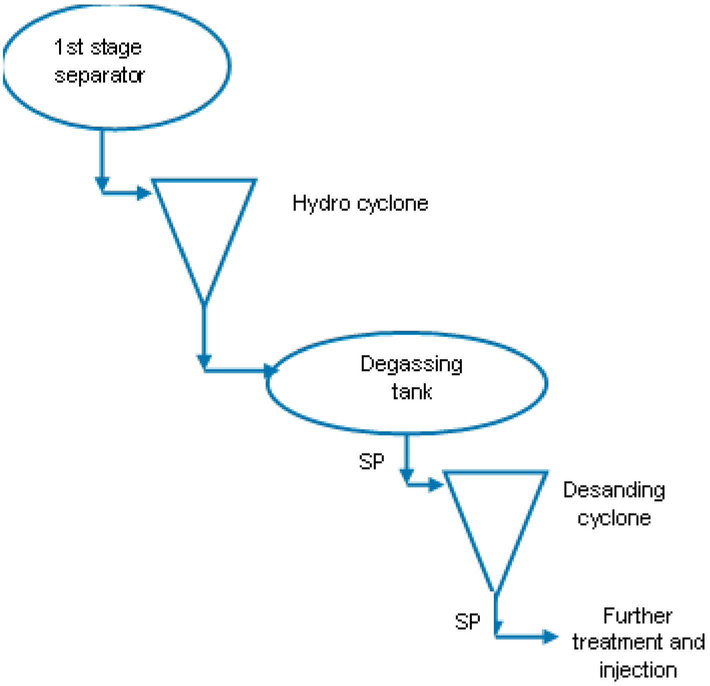


Figure 7-3: An overview of the produced water treatment system in Case 6, with a hydro cyclone, degassing tank, the desanding cyclone and further treatment before re-injection of the produced water. SP = sample point.

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[1] Relates to the first measured value upstream, 52 µm.

During the execution of this test the focus was on the solid particles and not on oil droplets and oil content and therefore no direct oil droplet measurement results are available.
The particle size distribution curves with oil, from samples taken different places in the system were available and are shown in Figures 7-4 and 7-5. These curves show the solid particles and the oil droplets as one, in the same curve. These figures illustrate samples taken at two different periods of time, with Figure 7-4 showing the particle size distribution (ppm vol) with oil for period 1.

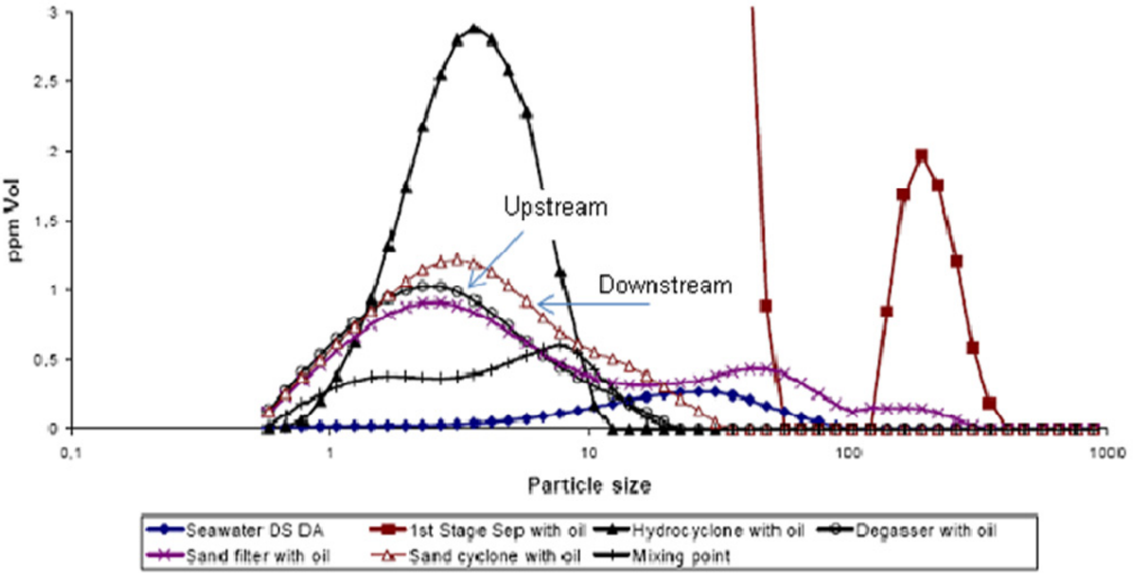

Figure 7-4: The particle size distributions (ppm vol) with oil for period 1, Case 6, showing the curve for the samples downstream the degassing tank (upstream) and the curve for the samples downstream the desanding cyclone (downstream).

Figure 7-4 indicates that the droplet size increases over the desanding cyclone, with the downstream curve showing the distribution shifted to the right.

Figure 7-5 shows the particle size distribution (ppm vol) with oil for period 2.

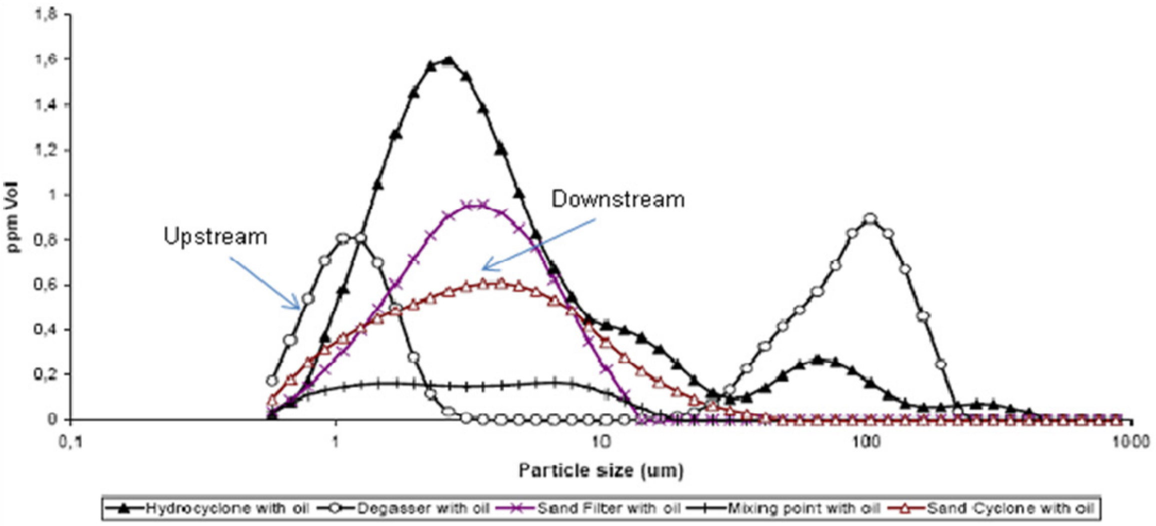

Figure 7-5: The particle size distributions (ppm vol) with oil for period 2, Case 6, showing the curve for the samples downstream the degassing tank (upstream) and the curve for the samples downstream the desanding cyclone (downstream).

The particle size distribution upstream the desanding cyclone (degasser with oil) shows two peaks at 1 µm and at 100 µm, while distribution of the particle sizes downstream the desanding cyclone shows the larger part of the droplets being smaller than 10 µm.

7.3 Discussion

7.3.1 Literature survey

Little work has been done with regards to the effect of desanding cyclones on oil droplet break-up and coalescence.

Former Krebs Engineering is the only contacted supplier that has performed tests, while the other suppliers base their statements on experience. Some stated that they have witnessed coalescence and others that they have witnessed better performance of the hydro cyclone when the desanding cyclone is in operation. As BP stated the latter might be the result of reduced clogging of the liners in the hydro cyclone, just as well as coalescence of oil droplet in the desanding cyclone.

The tests of Krebs Engineering supports the theory of high shear in the inlet of cyclones, as shearing only took place at large droplet sizes (> 35 µm) and at high flow rates. Experiments performed by Husveg (2007) supports the effect of the inlet droplet size in a cyclonic device, showing that the droplets will increase in size until a certain threshold inlet droplet size. He also showed that the coalescing tendency decreases with the flow rate, but that at lower flow rates larger droplets avoid break-up.

As the paper from Krebs Engineering was not available by the end of this thesis, it wasn’t possible to look further into the results. The report by Rawlins and Hewett (2007) could support that the desanding cyclone creates coalescence, but the increased performance in the separator could be caused by other indirect factors of the desanding cyclone, like less solids for the oil to stick to and to create steric hindrance.

7.3.2 Offshore experiments

One element of uncertainty that is relevant for all three cases is the effect of pipe coalescence. As some distance from the sampling points to the inlet of the desanding cyclones is known or assumed, there will be some uncertainty with regards to the actual inlet droplet sizes at the desanding cyclones inlets. Also, bends and restrictions in the pipes that could create shearing of droplets have not been evaluated here.

Looking at Case 1, the increase in droplet size ($D_{v,\ 50}$), from 2 – 4.3 µm to 8.9 µm across the desanding cyclone is a strong indication of coalescence.

The droplets upstream the desanding cyclone are of a size range that is less subjected to shearing. This would favor coalescence, and may explain the increase in droplet size.

The decrease in oil concentration from 80-110 ppm to 70 ppm over the desanding cyclone could indicate that some oil droplets have stuck to the solids and been removed with the underflow. The decrease could also be a result of dynamic differences during sampling, as the sampling upstream and downstream the desanding cyclone isn't performed at exactly the same time. The decrease in the oil concentration is either way an element of uncertainty with regards to the measured droplet sizes.

Case 2 indicates droplet break-up with the decrease in droplet size ($D_{v,\ 50}$), from 4.2 to 3.8 µm across the desanding cyclone (ratio = 0.9). The test referred to in Case 2 showed similar droplet sizes throughout the whole system. This is an uncertainty when evaluating the effect of the desanding cyclone on the oil droplets, for example could this size difference be dynamic differences between sampling.

The droplets are of a size range that is less subjected to shear, which would favor coalescence. Still the droplets are dispersed further.

Case 2 shows an increase in the oil concentration over the desanding cyclone. This could be the result of oil being torn off the solids within the desanding cyclone, or it could be a result of dynamic differences during sampling. The two oil concentration measurements upstream the desanding cyclone show quite different results, indicating dynamic differences. This also strengthens the possibility of dynamic differences causing the decrease in droplet size across the desanding cyclone.

The desanding cyclone in Case 2 has four outlets, and the sampling point downstream the desanding cyclone is located at a pipe where only three of these outlets have been gathered. This increases the uncertainty connected to both droplet size and concentration, as some part of the flow measured at the inlet wasn't measured at the outlet. It is possible that the droplet size distributions from all the outlets are similar, but this will just be speculations.

In Case 6 the desanding cyclone is located downstream the degasser as a part of the treatment for produced water re-injection. This should give the water other properties than in Cases 1 and 2, for instance lower oil concentration.

Figure 7-4 indicates coalescence with an increase in the droplet size distribution from downstream the degasser to downstream the desanding cyclone. The peaks at 1 µm and 100 µm at the curve representing the distribution downstream the degasser, in Figure 7-5, are assumed to be caused by noise from the measurements and gas bubbles, respectively. It's likely that if these peaks had been removed, the curve would have resembled the curve in Figure 7-4 showing an increase in the droplet size distribution and indicating coalescence.

The analyst informed that a flocculant had been used upstream the hydro cyclone. The effect of this flocculant should have happened in the degassing tank, but if the effect delayed the increasing droplet sizes over the desanding cyclone could be partly an effect of the flocculant.

Comparing the cases, Figure 7-6 shows the effect of the desanding cyclones in Cases 1 and 2 on the oil droplets.

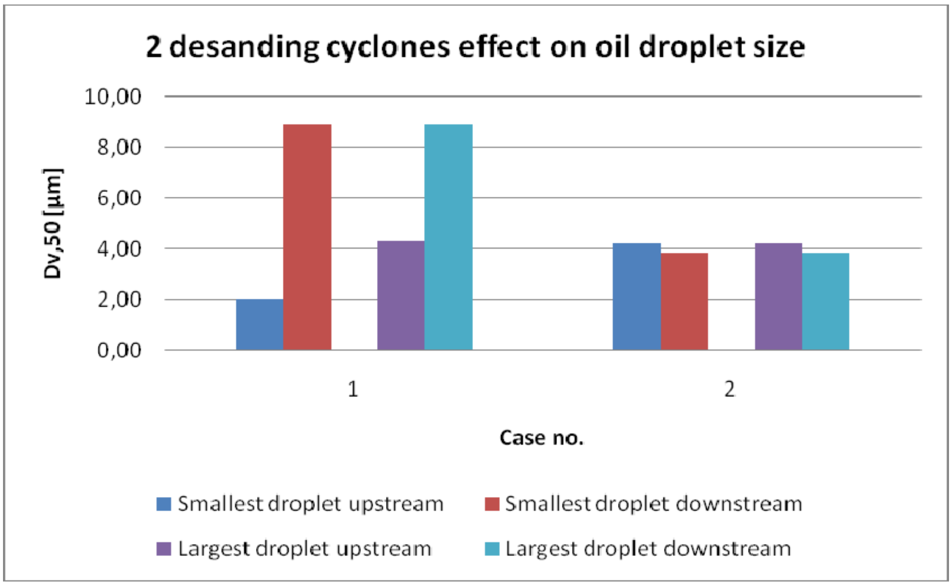

Figure 7-6: The droplet size ranges ($D_{v,\ 50}$) upstream and downstream the desanding cyclones in Cases 1 and 2. The figure is based on Table 10-11 in Appendix K.

Figure 7-6 shows that the droplet sizes upstream the desanding cyclone are similar in Cases 1 and 2, but that Case 1 might have a smaller $D_{v,\ 50}$ in the total flow going into the desanding cyclone. In Case 1 it's assumed that the flow from the 1st stage separator, which has the largest droplets upstream, is larger than the flow from the 3rd stage separator and that the droplets from the 1st stage separator will dominate in the total distribution. It's therefore assumed that the total $D_{v,\ 50}$ is similar to that of Case 2. Still the two cases show different effect on the droplet sizes, with Case 1 indicating coalescence and Case 2 indicating droplet break-up.

The sizes of the desanding cyclones in Cases 1, 2 and 6 are 3"-4", while Krebs Engineering tested 2" and 4" cyclones. These cyclones can be viewed as similar in size. As the Krebs Engineering test showed that break-up didn't occur until the droplet size reached 35 µm, it can be assumed the droplet sizes present here favor coalescence rather than droplet break-up.

The cases contain different degree of available data and factors that might be sources of error when evaluating the results. However, the three cases reviewed have shown coalescence or an assumable insignificant degree of droplet break-up. The results of these cases therefore support the conclusion from the Krebs Engineering test; that the desanding cyclone doesn't seem to damage the oil removal performance in the downstream equipment.

7.4 Recommendations for further work

The effect of the desanding cyclone on oil droplet break-up and coalescence should be further looked into, to evaluate the location of the desanding cyclone before the hydro cyclone.

This thesis gives an overview of the work that has been performed upon today and the results from this work. The offshore tests referred to in this thesis have not been performed with the intention to look into the effect of the desanding cyclone on oil droplets, and therefore sources of error are present making it impossible to make clear conclusions from the results. Although the suppliers state to have witnessed coalescence over the desanding cyclone it would be beneficial to have results to document this.

More knowledge could be acquired on the different systems and typical inlet droplet sizes in a desanding cyclone, as the inlet size is assumed to be important with regards to shearing.

Specifically designed tests should be performed within a lab to make it possible to change operational conditions and rule out as many uncertainties as possible.

8 Conclusion

Little work has been performed with regards to the effect of pumps on oil droplet coalescence and break-up.
The pump suppliers seem quite united in the fact that eccentric screw pumps generate the least droplet break-up. Most of them also find the twin screw pump to be gentle to the oil droplets. Their general impression is that the centrifugal pumps cause droplet break-up and don't measure up against the other pumps with regards to shear.
The literature survey reveals that previous tests indicate that a correctly sized and operated centrifugal pump could limit and eliminate shearing of oil droplets. Tests revealed by this literature survey ranked the twin screw pump below the centrifugal pump with regards to shear.

The offshore tests of centrifugal pumps indicate consistent shearing of the oil droplets. The tests show that the shearing increases with higher differential pressure and larger droplet sizes at the inlet. No data was available to see the effect of pipe coalescence downstream the pumps.

The offshore tests of the twin screw pumps indicates that the twin screw pumps coalesce smaller droplets and break up larger droplets (> ~7 μm).
The tests show that the there was no correlation between the differential pressure and the droplet size ratio over the pump. No conclusion can be made regarding the effect of pipe coalescence downstream of the pumps.

The offshore tests show that the twin screw pumps are better than the single stage centrifugal pumps with regards to shearing of oil droplets. These tests show that the twin screw pumps are more suitable for the boosting of produced water to a hydro cyclone.

The desanding cyclone suppliers have in general performed little work with regards to the desanding cyclones effect on oil droplet coalescence and break-up. The suppliers seem to agree that the desanding cyclone show a degree of coalescence.

The one revealed test show that droplet break up only occurs at droplet sizes above 35 μm and at high flow rates, and that the desanding cyclone is not damaging to the downstream separation.

The offshore tests indicate that the desanding cyclone create coalescence or an insignificantly degree of break up, and will not damage the oil removal performance of the downstream equipment.

9 References

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10 Appendixes

Appendix A: Best available techniques (BAT)

The treatment of produced water is often divided into primary, secondary and tertiary treatment. Equipment selection is based on the oil droplet size and the oil concentration in the initial produced water. Figure 10-1 gives an overview of the best available techniques (BAT) as given by OSPAR, categorized as mentioned above, and including an advanced treatment step (Vik 2009).

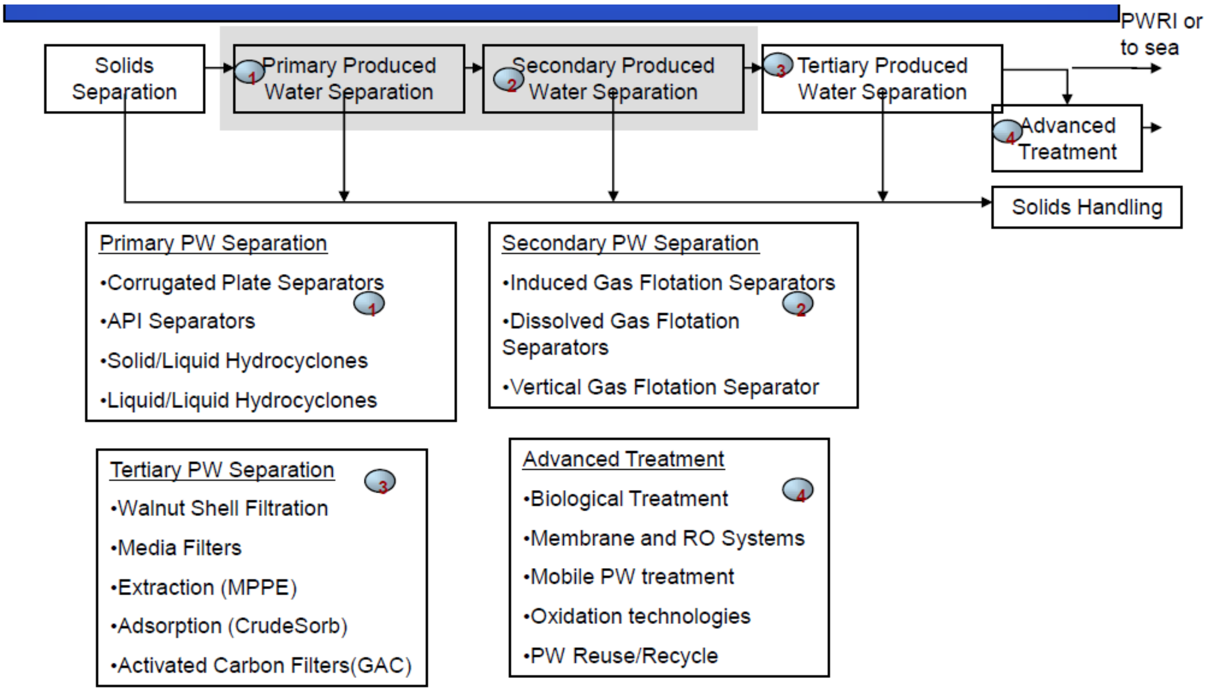

Figure 10-1: Overview of the best available technologies (BAT) as given by OSPAR, categorized as primary, secondary, tertiary and advanced produced water treatment (Vik 2009).

Appendix B: The impact of the chemical dosage rate

Table 10-1 shows examples of how the dosage rate of the chemicals can affect the separation and the produced water quality (Hustad 2009).

Table 10-1: Examples of effects using the incorrect dosage of chemicals, on the separation and produced water quality (Hustad 2009).

Chemical	**Dosage rate based on**	**Too low dosage rate**	**Too high dosage rate**
Emulsion breaker	Total production rates = Oil + water	Loss of phase separation	Loss of phase separation Emulsion breaker stabilized emulsion Increased WiO* og OiW*.
Naphtenate inhibitor		Naphtenate deposits	
Scale inhibitor	Water rate	Scale and scale particles	Increased consumption
Defoamer	Oil rate Total production rates = Oil + water	Foam. Challenge with level control Shut down	Increased consumption
Flocculant	Water rate	Increased OiW values	Clogging of rejects and increased OiW
Corrosion inhibitor	Total production rates = Oil + water	Corrosion	Increased OiW
Wax inhibitor	Total production rates = Oil + water	Wax deposits	Increased consumption Increased OiW
Asphaltene inhibitor	Total production rates = Oil + water	Deposits of asphaltenes	Increased consumption
Hydrate inhibitor	Water rate	No inhibition	Increase OiW and WiO

*WiO and OiW are water in oil and oil in water concentrations respectively.

Appendix C: The classification of rotary and dynamic pumps

A basic system of classifying pumps is to first define the principle, by which the energy is added to the fluid, then identify the means of which the principle is implemented and finally identify the specific pump geometries. Pumps dealt with in this thesis belong to the major pump groups dynamic (kinetic) and rotary pumps.

Figure 10-2 and Figure 10-3 show the further classification of these groups as given by the Hydraulic Institute.

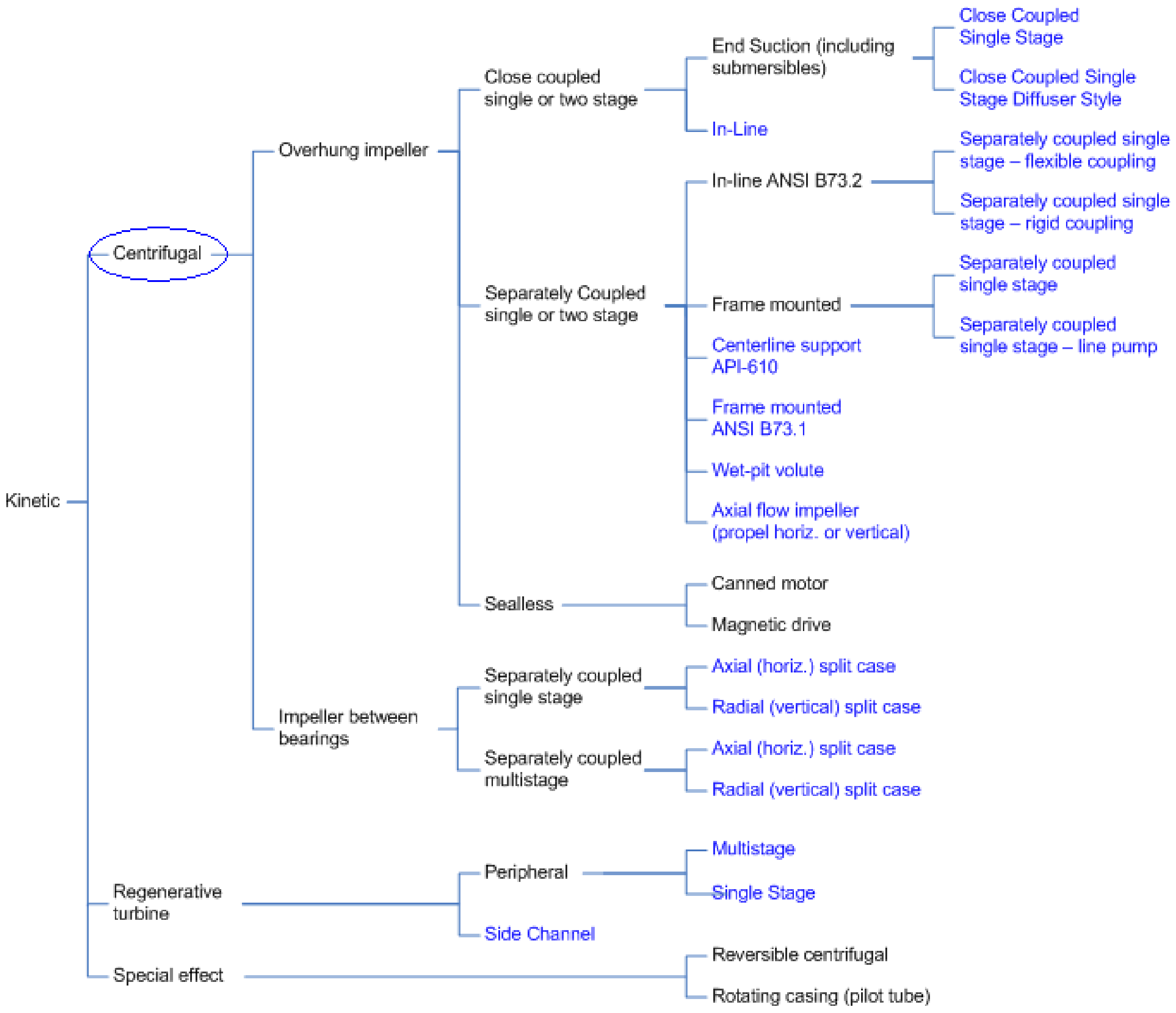

Figure 10-2: Overview of the different types of dynamic pumps (Hydraulic Institute).

Appendix C: The classification of rotary and dynamic pumps, continued.

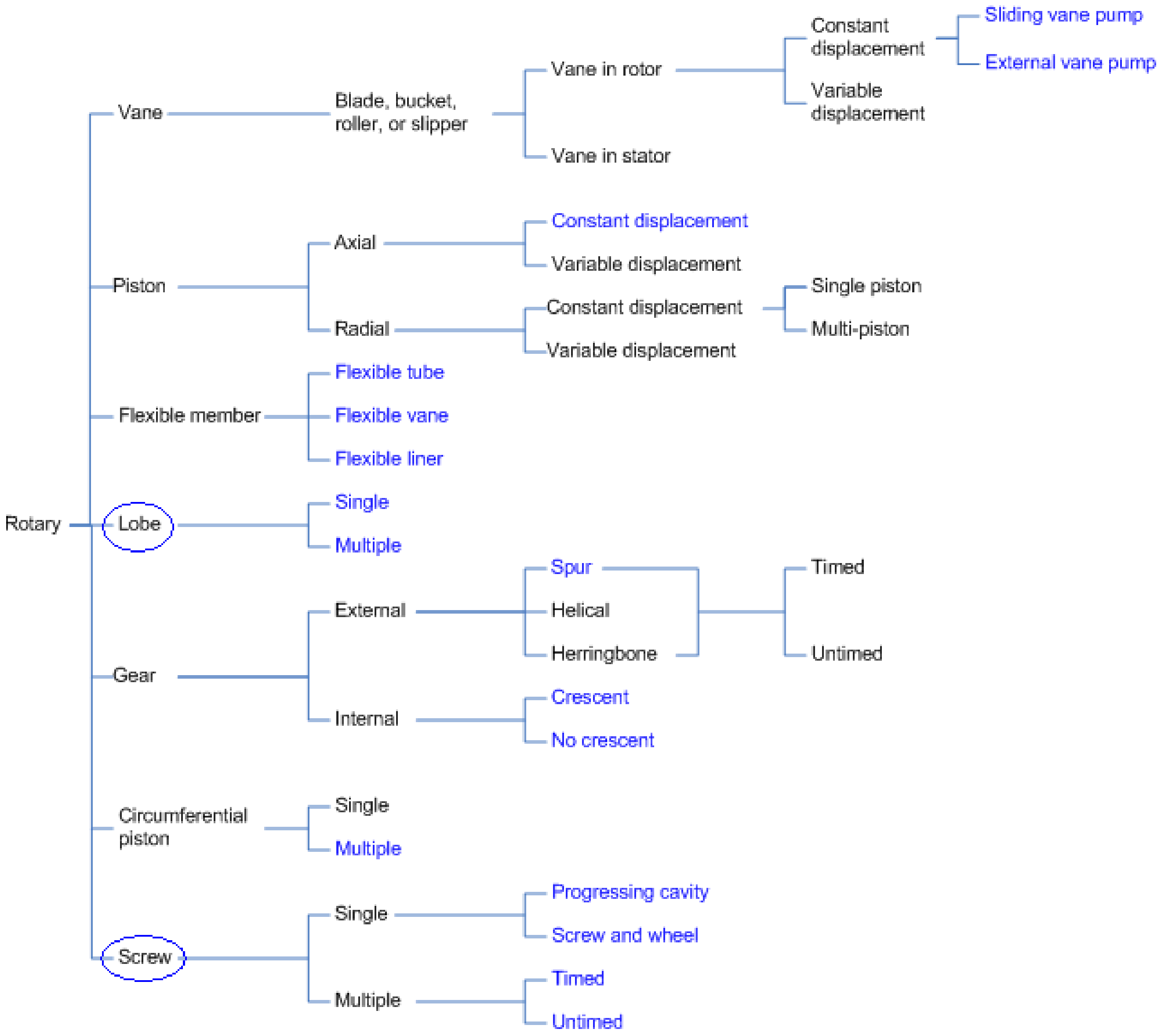

Figure 10-3: Overview of the different types of rotary pumps (Hydraulic Institute).

Appendix D: List of contacts

Throughout this thesis many persons within many companies have been contacted. Table 10-2 shows the complete list of people that have been contacted.

Table 10-2: Overview of the people and companies that have been contacted during this thesis.

Company	**Surname**	**First name**
PG Marine Group - Ing Per Gjerdrum AS	Eide	Anders
Bjørge AS	Larsson	Lars Erik
Bjørge AS	Nord	Steinar
Bjørge AS	Rønning	Per
Seepex	Williams	Simon
Sulzer	Germaine	Brian
Petreco Process Systems / Cameron	Abraham	Nigel
CETCO Oilfield Services Company	McPhilemy	Edward
Cyclotech	Hess	Michael
Axflow	Haugmo	Svein
Axflow	Bangen	Ole-Petter
Axflow		
KGD Process International	Gould	Peter
Enhydra Ltd	Lloyd	David
Merpro	Podger	Tim
Cyclotech	Corsie	Malcolm
Moxley	Salter	Paul
FLSmidth	Thorogood	John
Natco Norway	Christiansen	Bjørn

Alderley	Blewett	Amanda
Total E&P Norway	Goldszal	Alexandre
Total E&P Norway	Moltu	Ulf Einar
ConocoPhillips	Voldum	Kåre
Shell	Edvardsson	Trym
ExxonMobil	Bjørkevoll	Inge
ExxonMobil	Moss	Rigmor
BP	Markoff	Christina
BP	Sweeney	Frank
Opus Plus	McLellan	Glen
Opus Plus	Giles	Lorraine
Mator	Finborud	Anne
Mator	Dybvik	Camilla
Mator	Kjærstad	Kristian
Aker Solutions	Hana	Morten
Aker Solutions	Seereeram	Shanta
Aker Solutions	Løken	Karl-Petter
Aker Solutions	Kirkeng	Nina-Christine
Aker Solutions	Brodersen	Morten
Aker Solutions	Vollar	Christoffer
Aker Solutions	Viland	Kristine
Aquateam	Vik	Eilen
Typhonix	Husveg	Trygve
ProCom / CTour	Henriksen	Inge Brun
Grenland Group / xHydro	Gramme	Per Eivind
StatoilHydro	Solsvik	Olav

StatoilHydro	Arvesen	Torunn
StatoilHydro	Nordnes	Anders
StatoilHydro	Holden	Randi
StatoilHydro	Lie	Gunnar Hannibal
StatoilHydro	Jensen	Tord
StatoilHydro	Knudsen	Børre Leif
StatoilHydro	Nyborg	Petter Johan
StatoilHydro	Teigland	Morten Andre
StatoilHydro	Lohne	Kjell
StatoilHydro	Hustad	Britt-Marie

Appendix E: List of literature reviewed in addition to those cited

This list shows the literature that has been reviewed in this thesis, but that didn’t give results or hasn’t been cited.

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Appendix F: Test program made for Case 2 – desanding cyclone

A test program was made for the measurements concerning this thesis in relation to an offshore trip made by Mator.

The test program is shown below.

<u>Test series:</u>

1. Droplet size measurements: Upstream and downstream the desanding cyclone, 3 sample series with 30 minute intervals.

2. Oil in water concentration: Upstream and downstream the desanding cyclone, 3 sample series with 30 minute intervals.

If major changes of the operational parameters occur during the sampling period, it would be beneficial to perform some more tests.

Description of the sample points and there distances to the desanding cyclone is wanted.

Appendix G: Test program made for Case 1 – desanding cyclone

A test program was made for measurements to be proposed executed at the laboratory of the field in Case 1. This test wasn't executed during this thesis.
The test program is shown below.

Sample points:
1 upstream the hydro cyclone
1 downstream the hydro cyclone

Test series:

1. With desanding cyclone in operation: Oil in water concentration upstream and downstream the hydro cyclone, 3 sample series with 30 minute intervals.

2. Bypassing the desanding cyclone: Oil in water concentration upstream and downstream the hydro cyclone, 3 sample series with 30 minute intervals.

Sampling upstream and downstream the hydro cyclone must be done as simultaneously as possible. In the period of sampling the operation must be as stabile as possible. During the bypassing of the desanding cyclone, no changes must be made to the hydro cyclone.

Appendix H: Centrifugal pumps; test results and operational data

The different tests on centrifugal pumps are noted Case X (X=1, 2...). Table 10-3 gives the overview of the four cases available and their respective test results and available operational data.

Table 10-3: Overview of the test results for the centrifugal pump cases, including the operational data available.

Case no.	**Upstream ($D_{v,\,50}$)**	**Downstream ($D_{v,\,50}$)**	**Droplet size ratio**	**Oil in water concentration**	**Load**	**Inlet pressure**	**Outlet pressure**	**ΔP**
	[µm]	[µm]		[ppm]	[m³/h]	[barg]	[barg]	
1	8	2,5	0,3125	84	24	2,2	14	11,8
2	3,8	3,8	1	56/28	3	1,1	7	5,4
3	4,65	3,2	0,688	160	15-25	1,1	11	9,9
4	13,83	11,25	0,813	-	-	-	-	-

For Case 4 three parameters was available: $D_{v,\,10}$, $D_{v,\,50}$, $D_{v,\,90}$. The upstream and downstream values of these parameters are given in Table 10-4.

Table 10-4: Overview of the complete test results for Case 4.

[µm]	**$D_{v,\,10}$**	**$D_{v,\,50}$**	**$D_{v,\,90}$**
Upstream	5,29	13,83	23,84
Downstream	6,68	11,25	18,52

Appendix I: Twin screw pumps; test results and operational data

Case 5 is the two tests of the twin screw pumps noted 5a and 5b.

Table 10-5 and Table 10-6 give the overview of the test results and available operational data for Case 5a and Case 5b respectively.

Table 10-5: Overview of the test results for the Case 5a, including the operational data available.

Produced water source	Twin screw pump	Upstream ($D_{v,50}$)	Downstream ($D_{v,50}$)	Oil in water concentration	Load
		[μm]	[μm]	[ppm]	[m³/h]
1st stage separator	F	7	6,8	360	137
2nd stage separator	B	5,1	7,2	160	252
El. Coalescer B	D	7,4	6,8	96	71
El. Coalescer A	C	5,4	7,6	95	71

Table 10-6: Overview of the test results for the Case 5b, including the operational data available.

Produced water source	Pump	Upstream [μm]		Downstream [μm]		Oil in water concentration	Load	Inlet pressure	Outlet pressure	ΔP	Speed
		$D_{v,10}$	$D_{v,50}$	$D_{v,10}$	$D_{v,50}$	[ppm]	[Sm³/h]	[barg]	[barg]		[rpm]
1st stage separator	F	0,935	4,9525	1,0215	6,1475	159	92	7,9	11,87	3,97	379
2nd stage separator	A	0,99	5,0575	1,0875	6,345	108	218	3,3	12,14	8,84	809
El. Coalescer B	D	1,23	3,905	1,365	8,6825	49	86	3,1	12,13	9,03	461
El. Coalescer A	C	1,595	5,145	1,14	4,615	39	109	3,1	12,08	8,98	521

Appendix I: Twin screw pumps; test results and operational data, continued

The most important droplet sizes are the size of the droplets in the inlet flow of the hydro cyclone. Table 10-7 gives the droplet sizes downstream the twin screw pumps and upstream the two hydrocyclones A and B in Case 5b. The droplet sizes downstream the pumps are calculated values to represent the droplet sizes in the total fluid flow being routed to the hydrocyclone.

Table 10-7: Overview of the droplet sizes downstream the pumps and upstream the hydrocyclones A and B in Case 5b.

Dv, 10			Dv, 50		
d/s pump	u/s HC A	u/s HC B	d/s pump	u/s HC A	u/s HC B
1,133	1,2125	1,4175	6,409	7,559	6,6225

Table 10-8 gives the droplet size ratios along with the differential pressure.

Table 10-8: Overview of the droplet size ratios for $D_{v,\ 10}$ and $D_{v,\ 50}$ values, and the differential pressure for the twin screw pumps in Case 5b.

Produced water source	Pump	ΔP	Droplet size ratio	
			$D_{v,\ 10}$	$D_{v,\ 50}$
1st stage separator	F	3,97	1,092513	1,241292
2nd stage separator	A	8,84	1,098485	1,254572
El. Coalescer B	D	9,03	1,109756	2,223431
El. Coalescer A	C	8,98	0,714734	0,896987

Appendix J: Comparison of twin screw pumps and centrifugal pumps

The centrifugal pumps and twin screw pumps (both 5a and 5b) and their effect on the droplet sizes are compared. Table 10-9 gives an overview of the droplet size $D_{v,\ 50}$ values and the droplet size ratio of all the pumps reviewed in this thesis.

Table 10-9: Overview of all the pumps reviewed; centrifugal and twin screw pump, with their droplet sizes and droplet size ratios.

Produced water source	**Pump**	**Upstream [µm]**	**Downstream [µm]**	**Droplet size ratio**
		$D_{v,\ 50}$	$D_{v,\ 50}$	
Centrifugal	1	8	2,5	0,3125
Centrifugal	2	3,8	3,8	1
Centrifugal	3	4,65	3,2	0,688172043
Centrifugal	4	13,83	11,25	0,813449024
Screw pump (5a)	F	7	6,8	0,971428571
Screw pump (5a)	B	5,1	7,2	1,411764706
Screw pump (5a)	D	7,4	6,8	0,918918919
Screw pump (5a)	C	5,4	7,6	1,407407407
Screw pump (5b)	F	4,9525	6,1475	1,241292277
Screw pump (5b)	A	5,0575	6,345	1,254572417
Screw pump (5b)	D	3,905	8,6825	2,223431498
Screw pump (5b)	C	5,145	4,615	0,896987366

Appendix K: Desanding cyclones; test results and operational data

The different tests on the desanding cyclones are noted Case X (X=1, 2...). The numbers are connected to the notation of the pumps. Table 10-10 gives the overview of the three cases available and their respective test results and available operational data.

Table 10-10: Overview of the test results and the available operational data from the desanding cyclone tests.

Case	**Upstream [µm]**		**Downstream [µm]**		**Load**
	Concentration	$D_{v,\ 50}$	Concentration	$D_{v,\ 50}$	[m^3/h]
1	80-110	4,3 / 2-3	70	8,9	276
2	52 / 127	4,2	78 / -	3,8	94
6	8,3 / 26	Diagram*	/ 28	Diagram*	-

* Results only available in the diagrams presented in Chapter 7.2.3.

Table 10-11 gives the overview of the droplet size ranges for Cases 1 and 2.

Table 10-11: Overview of the droplet size ranges upstream and downstream the desanding cyclones in Cases 1 and 2.

	Smallest sizes ($D_{v,\ 50}$)		**Largest sizes ($D_{v,\ 50}$)**	
Case no.	Upstream	Downstream	Upstream	Downstream
1	2,00	8,90	4,30	8,90
2	4,20	3,80	4,20	3,80