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New Method for Improving Oil Droplet Growth for Separation Enhancement

Anne Finborud, Mator AS, Mark Faucher, SPE, and Erik Sellman, SPE, Alfa Laval Oilfield

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Abstract

Produced water quality is a function of the reservoir conditions, the fluid chemistry and the upstream process. The oil droplet size distribution in produced water is influenced mainly by choke valve pressure drop causing shear effects thereby droplet break down, and further the oil droplets ability to coalesce to larger droplets. Factors preventing coalescence include the droplets negative electrostatic charge, stabilization by surface active components and steric stability caused by fines. The larger the oil droplets in the produced water the easier they are to separate (Stokes' Law). Hydroflok is a newly developed process for pre-treatment of produced water in order to optimize its separability. In this process oil droplets are subjected to combined chemical and mechanical action to accelerate coalescence and the formation of larger, more separable flocs.

The Hydroflok system was developed by Norsk Hydro on behalf of the Troll Oil Unit Committee, to be qualified for installation on the Troll B platform in the North Sea. There the Hydroflok system has been operated successfully since the installation in March 1996. The system has successfully been tested at several offshore platforms with a containerized test unit and has been incorporated in the produced water system for the Troll C platform to go on stream in 1999/2000.

Introduction

The allowable concentration of oil in overboard water vary in different parts of the world; 29 and 40 ppm are common limits, but lower levels are actively discussed. By using conventional equipment the discharge limit is often difficult to achieve and reaching lower limits is usually impossible. Future challenges facing these systems include:

- Increased water cuts with reduced residence time, multi-droplet coalescence and water continuous systems.
- New installations with high density viscous oil.
- Lower operating pressures.
- Increased volume of reject streams.
- Common use of enhanced oil recovery.
- Use of artificial lifting

The composition and properties of produced water vary significantly between different fields. Variations in water cuts, choke pressures and other fluid parameters effect the produced water quality. Even under favorable conditions, oil droplets smaller than 10 μm are difficult to separate. Small droplets may represent such high proportion of the oil content that it is impossible to achieve the discharge specification. The original objective of the treatment system to meet the discharge limit without the use of chemicals is rarely met. The use of chemicals is often inefficient due to low retention time and inadequate mixing.

The Hydroflok process was developed to create more stable and easier to separate flocs. The benefits of using the Hydroflok system are increased separation efficiency and reduced or eliminated chemical consumption.

Produced Water Treatment – Problem Definition

Produced water treatment systems based on mechanical separation can remove oil droplets and continuous oil films from produced water. Whereas a continuous oil film is easy to remove from the produced water with most treatment methods, small oil droplets can be very difficult to remove.

Oil Droplet Size. Stokes' Law determines the settling velocity of an oil droplet, as described below:

$$v_s = \frac{d^2 (\rho_w - \rho_o)}{18 \eta} g$$

- where:
- v_s = the oil droplet settling velocity (m/sec)
 - d = the oil droplet diameter (m)
 - ρ_w = the water density (kg/m³)
 - ρ_o = the oil density (kg/m³)
 - η = the water viscosity (kg/m,sec)
 - g = the g-force applied (m/sec²)

Small oil droplets will settle much slower than large oil droplets. Field experience has shown that the oil droplet size distribution often has a peak around 10 – 15 μm and thus the volume of oil droplets below 10 μm can be quite significant. According to Stokes' Law, the settling velocity is proportional to the square of the oil droplet diameter and to the g-force applied. Fig. 1 shows required time for API^o 20 oil droplets to rise/settle one inch in water, as a function of the size of the oil droplet and the g-force applied.

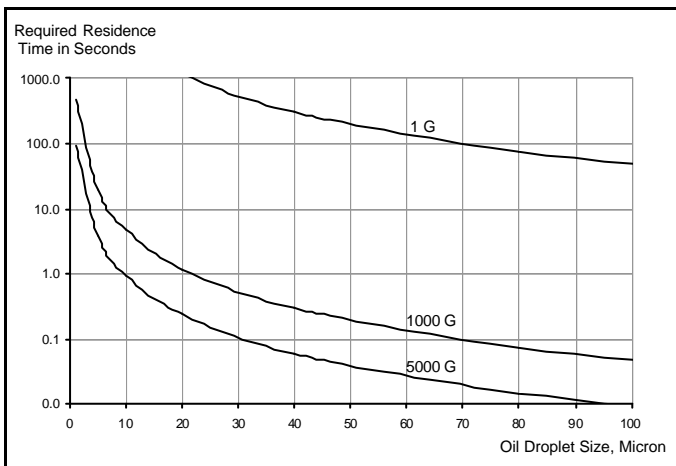


Fig.1 Time required for one API^o 20 oil droplet to settle one inch in 1 cSt water.

Oil droplet size is crucial to separation and it is imperative that the selected equipment is suitably effective. The smaller the droplets, the lower their settling velocity. The separation equipment can be made more effective by increasing the g-force applied on the oil droplets. It may also be possible to increase the settling velocity of the oil droplets by flocculating them into larger agglomerates.

Oil Droplet Generation. Fig. 2 shows a typical size distribution of oil droplets in produced water downstream of a 1st stage separator.

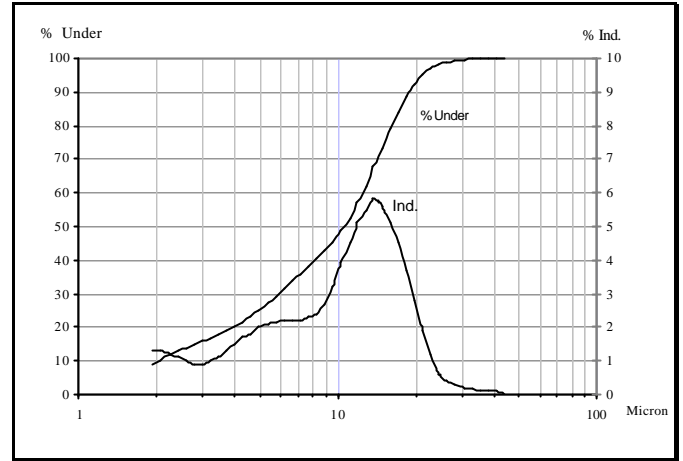


Fig. 2 Typical Oil Droplet Size Distribution, $d_{v50}=10 \mu\text{m}$.

d_{v50} is the average oil droplet size by volume. The oil droplet size distribution is a function of the upstream process, the fluid chemistry and the reservoir conditions. Pressure drops in process equipment cause oil droplet break down due to the energy dissipation around the restrictions in the equipment (chokes, control valves, inlet devices in vessels, hydrocyclones, etc.). Fig. 3 shows the main mechanism of droplet break down in a choke valve.

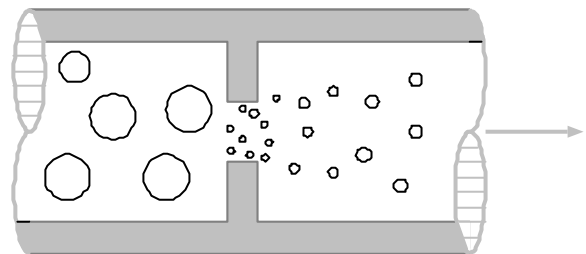


Fig. 3 Droplet break down in choke valves

The choke valve with the highest pressure drop in the process has the largest impact on the size of oil droplets generated. Fig. 4 shows average diameter of oil droplets generated as a function of the pressure drop across the equipment. As can be seen from the curve, even moderate pressure drops like 150 psi can generate oil droplets below 10 μm. This curve is also relevant for oil droplets sheared by centrifugal pumps.

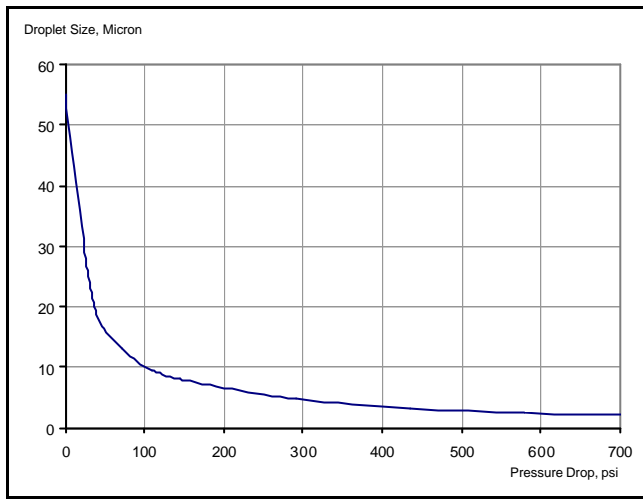


Fig. 4 Average droplet size as a function of pressure drop

Influence of Production Chemicals. Another factor which influences the degeneration of oil droplets is the droplets' interfacial tension, since a reduction in interfacial tension leads to easier droplet break down. O.J. Hinze found that the max. diameter of oil droplets can be expressed as:

$$d_{max} = C \frac{\sigma^{0.6}}{\epsilon^{0.4} \rho^{0.2}}$$

- where:
- C = correction factor (0.725)
 - σ = interfacial tension (10^{-2} dynes/m)
 - ϵ = energy dissipation (1/sec)
 - ρ = density of continuous phase (kg/m^3)

Production chemicals that have a negative influence on the interfacial tension, include corrosion inhibitors and Methanol. Produced water containing corrosion inhibitor and/or Methanol will contain higher concentrations of small oil droplets.

Oil Droplet Coalescence. If the conditions are right, many of the small droplets generated in the choke valve will coalesce to larger oil droplets. Factors that prevent or retard coalescence include:

- droplets repelling each other due to electrostatic charge
- stabilization by surface active chemicals
- steric stability caused by fine particulate matters adsorbed to the droplet surface

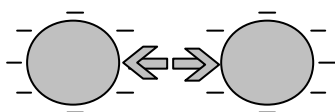


Fig. 5. Oil droplet repelling

The salinity of the produced water directly influences the electrostatic charge of the oil droplets, thereby affecting whether the oil droplets will coalesce or not, as shown in the chart below.

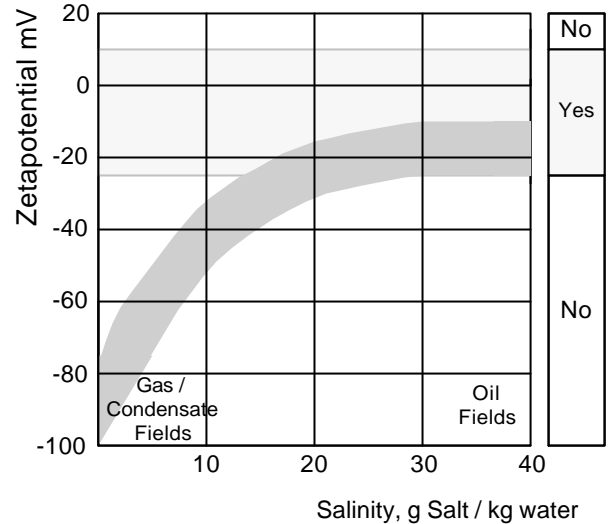


Fig. 6. Droplet coalescence as a function of water salinity

The droplet electrostatic charge is higher when the salinity is low, thus preventing coalescence. When the salinity is higher, say 2.5 % or more, the electrostatic charge is low and thus conditions for coalescence exist. Condensed water from gas condensate fields typically has a low salinity and thus often contains large amounts of very small oil droplets.

Particulate matters in produced water, like clay or scale, often adhere to the oil droplet surface and thus prevent natural coalescence through steric stability. Surface active chemicals have a similar negative effect on coalescence through reduced interfacial tension.

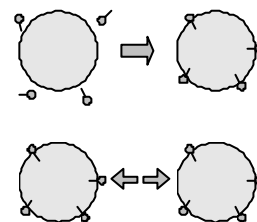


Fig. 7 Droplet repelling due to steric stability

Possible Solutions and Constraints

The only practical and reliable equipment for deoiling of produced water are based on gravity separation. The equipment efficiency depends on the g-force applied and the equipment internal settling distances. The time required to remove oil droplets is basically the settling distance divided by the settling velocity. The shorter the settling distance and the greater the settling velocity, the more effective the separation process.

Table 1. Equipment Comparison

Equipment	Driving Force	Settling Distance	Droplets Removed
Flotation Cells	1 g ¹	> 60 inches	> 20 micron
Hydrocyclones	~ 1000 g	> 0.4 inches	> 10 micron
Disc Stack Centrifuges	~ 6000 g	~ 0.02 inches	> 2 micron

¹ Enhanced by bubble flotation.

Gas flotation processes are thus suitable for easy to remove oil droplets only. Hydrocyclones have been the preferred option in new designs of North Sea installations due to their robustness, compactness and reliability. However, there are limitations as to:

- size of oil droplets which can be removed
- volumetric concentrations which can be handled
- acceptable turn down ratio
- what to do with the reject stream

Using hydrocyclones, 75% separation efficiency is typically attained for 8 – 10 µm oil droplets. This efficiency problem may be solved by use of chemicals for enhancing droplet growth. The traditional offshore process designs are far from being ideal in order to utilize the potential droplet growth that these chemicals offer.

Disc stack centrifuges are the only effective equipment to remove oil droplets below 10 µm. Due to the different operating windows, working principle and design, hydrocyclones and centrifuges should be regarded as complementary technologies.

Oil Droplet Growth for Enhanced Separation

The larger the oil droplets in the produced water, the easier they are to separate (Stokes' Law). The natural tendency to coalesce causes the droplets to grow to a certain extent. However, when the electrostatic charge is high due to low water salinity, or when surface-active chemicals are present, the droplets repel one another resulting in little or no coalescence. In these cases, the droplets can be encouraged to coalesce by destabilizing them using chemicals that have a positive charge and / or using flocculants that cause them to form larger, more separable flocs. In the Hydroflok process the oil droplets are subjected to an accelerated coalescence and the formation of larger flocs by means of combined chemical and mechanical action.

Description of the Hydroflok Process. In the Hydroflok process, the produced water from a separator is pre-treated in a flocculation vessel, prior to separation in hydrocyclones. The flocculation vessel consists of two chambers connected in

series in which the droplets are first enlarged and subsequently flocculated, as shown in Fig. 8.

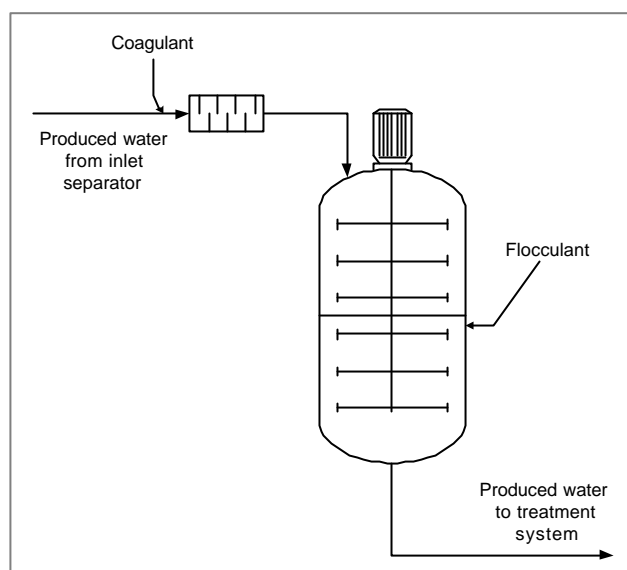


Fig. 8 Hydroflok Process

The electrostatic charge on the oil droplets is neutralized using of a coagulant. The coagulant is added as early as possible in the pipe upstream the flocculation vessel and immediately distributed in the water by means of a mixer. After mixing, the produced water enters the first chamber of the flocculation vessel where it is exposed to vigorous mixing over a defined retention time. The oily water then flows into the second chamber where a flocculant is added causing the small agglomerates to grow into larger flocs. The oily water is again subjected to vigorous mixing over a retention time optimized to achieve fast flocculation and the formation of strong and stable flocs, which are easy to remove in the subsequent separation stage. The flocs have to have sufficient strength to withstand the high shear forces in the hydrocyclone inlet.

The Hydroflok process operates at the same pressure as the upstream separator to avoid liberation of free gas and thereby optimizing the performance of the downstream hydrocyclones. The selection of chemicals, dosing rates, degree of turbulence (i.e. agitator speed) and retention time are crucial parameters for the process. Depending on the individual characteristics of the produced water to be treated, it may be possible to utilize only agitation, or agitation in combination with a single chemical injection to achieve the desired result.

As described above, the Hydroflok process combines the principles of coagulation and flocculation, resulting in:

- controlled growth of oil droplets
- formation of stable, robust flocs which can withstand the shear forces in hydrocyclone inlets
- reduced chemical consumption
- improved oil / water separation

Process development. The Hydroflok process was developed by Norsk Hydro during the conceptual phase of the Troll B project. The Troll Oil concept is a distributed sub sea system assumed to create water treatment problems due to high water cut, long subsea transport and possible flow disturbances in separators. Pipeline slugging and relative low temperature and short retention time in the first stage separator were all factors contributing to the water treatment problem. Several methods were evaluated in the initial conceptual design. The choice was made to install hydrocyclones, but to allow space for future improvements. Studies showed that improved hydrocyclone performance could be achieved by installing an upstream oil droplet flocculation process. Based on water with 1000 ppm oil droplets of an average size of 5 μm , pilot scale trials with a flocculation process upstream a hydrocyclone liner were carried out. The pilot study gave the following hydrocyclone separation efficiencies at the different operating conditions:

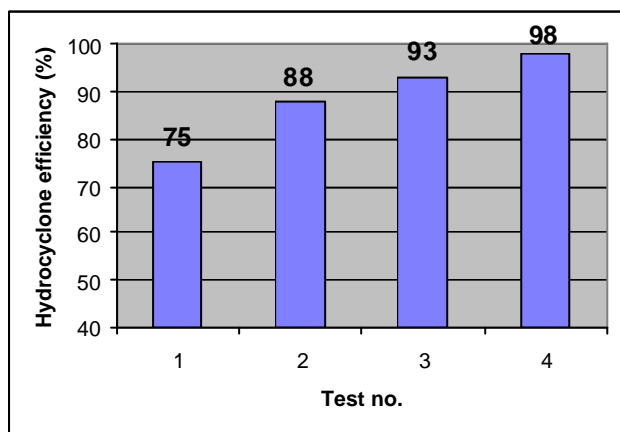


Fig. 9 Hydroflok pilot test results

Test no. 1: Hydroflok not included.

Test no. 2: Flocculation vessel included, no chemicals.

Test no. 3: One component system.

Test no. 4: Two component system.

The dosing rate with one component system was 5 ppm, and with two component system 1.5 ppm coagulant and 0.5 ppm flocculant, all as 100% active material. The total retention time (flocculation vessel + upstream/downstream pipelines) was 2.5 minutes. Based on the above very promising results, the Hydroflok process was installed at the Troll B platform. See section "Case stories" for operating experience.

Features. The Hydroflok process was developed to provide the following features:

- Controlled flocculation of oil droplets upstream the hydrocyclones. This to control formation of strong and stable flocs to withstand the shear forces in the hydrocyclone inlet. The hydrocyclone separation efficiency is highly improved.

- Potential for a produced water system which does not require the use of produced water chemicals. Further, the process may be operated as a one chemical component system or two component system, depending on the process requirements. In this way, the Hydroflok process provides high flexibility to the produced water treatment system.
- Produced water chemicals are often used in an inefficient way due to inefficient mixing. With the Hydroflok system the positive effect of the chemical is more effectively utilized thereby reducing the chemical consumption.
- Improved utilization of existing hydrocyclones of an older design.
- As the separability is improved, lower hydraulic load may be tolerated for the hydrocyclones at a given separation efficiency, i.e. the turn down ratio of the hydrocyclones will increase. The ability to handle normal flow fluctuation in the process without increase in the concentration of oil overboard is improved.
- Relative compact system thereby low footprint requirement for the Hydroflok system.
- The oil/water separation train may have the full priority. Production chemicals to improve water from oil separation could more widely be used if necessary without resulting in increased oil in water discharge to sea.

Typical application and project progress. The key to an effective and profitable process solution is to determine and understand the vital separation characteristics of individual components and their interaction within the entire process system. This may be obtained through a mapping survey of the process to provide an overview of performance and efficiency, explain the measured performance, and testing of solutions. The mapping activity may include:

- Optimize separator operations with respect to the produced water quality.
- Optimize hydrocyclone and degasser performance.
- Test and select the best performing produced water chemical, including adjustment of the dosage rate.
- Testing of alternative produced water equipment.
- Study the effects of recirculated streams on produced water quality.
- Testing and analysis of produced water with respect to reinjection.

During a mapping survey, the following tools may be used:

- Laser diffraction particle sizer (Malvern) for droplet size distribution measurements.
- Infra Red (IR) analyzer for oil in water measurements.
- The ProSep software program specially developed for calculations of produced water processes, based upon physical properties, process conditions, droplet size distributions and fluid chemistry.

For field verification of the Hydroflok process, a small test unit is available for rent. This unit is housed in a 10' container and is complete with a flocculation vessel, chemical dosing system, hydrocyclone liner and degassing drum. Used together with appropriate analytical tools this unit makes it possible to verify the optimal design and operation of a full-scale process.

The treatment of produced water is not a standardized process. Depending on the layout of the separation train, pressures, oil and gas content and size of the oil droplets and other factors, these plants are individually designed to be able to fulfil their duties properly with safe margins. Typical applications where the Hydroflok process should be evaluated may include the following:

- High amount of small oil droplets ($<10\ \mu\text{m}$)
- High concentration of oil in the water from the separator
- Large water volumes

The Hydroflok process is highly suitable for retrofitting hydrocyclone installations where the required separation efficiency has not been obtained.

Reject Treatment

The reject from the hydrocyclones typically represents 2 – 5% of the total produced water flow. Even if these reject streams have a higher oil concentration, they still contain 95 – 98% water. Reject streams are stable and have high concentration of very small oil droplets. This is caused by the shear across the reject control valve and the presence of stabilizing production chemicals and surface-active components. Recirculation of rejects to the main process will result in accumulation of water with very low separability thereby complicating the downstream water treatment system. Also, it may complicate the separation of water from the crude oil. It is therefore recommended that the hydrocyclone reject is treated separately in order not to interfere with the main process at the facility. Reject streams are best processed in a small centrifuge where the oil droplets are forced coalesced into a continuous oil phase which can be fed directly to the export pipeline. The separated water phase from the centrifuge is clean enough to be discharged overboard.

Case Stories

Troll B, Norsk Hydro. The produced water system at Troll B uses hydrocyclones for treatment of water from the 1st and 2nd stage separators together with a common degasser before discharge into the sea. The Hydroflok process is included for water from the 1st stage separator to enhance oil droplet growth upstream the 1st stage hydrocyclones. Rejects are recirculated by pumping to the main process upstream the 3rd stage separator. Water from the coalescer is recirculated by pumping to the 1st stage separator.

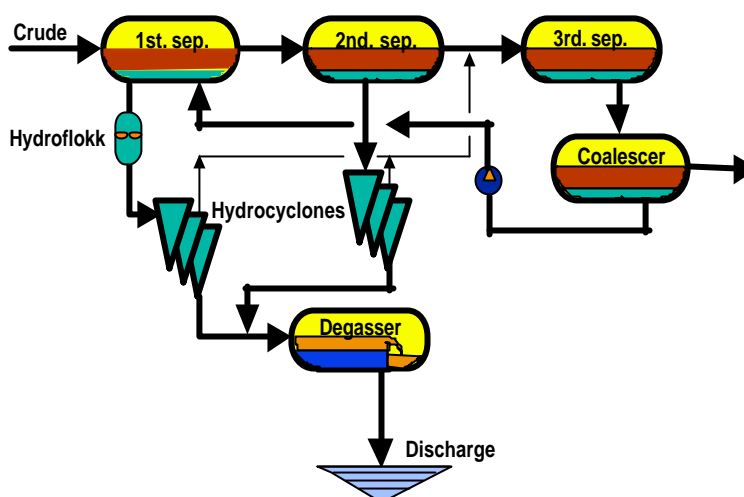


Fig. 10 Troll B process diagram

Troll B was started in September 1995 without Hydroflok installed. Produced water chemicals had to be added in the water (15 ppm Dyno WC-12) to fulfil the discharge limit of 40 ppm. Based on the very promising pilot test results, the Hydroflok process was installed in March 1996. After this installation, produced water chemicals were no longer required.

A mapping of the produced water system at Troll B, covering droplet size analyses with corresponding concentration measurements, was carried out in January 1997. In addition, a test with injection of flocculant Dyno WT-34 upstream the flocculation vessel was performed. The results showed the following:

- Total water production was about 20,000 m³/d (126 k Bbl/d, approx. 97% from the 1st stage separator) corresponding to 50% of the total design flow. The concentration of hydrocarbons in the produced water from the 1st stage separator was 1,000 - 1,400 ppm. Average discharge of non polar hydrocarbons overboard was approx. 23 ppm, i.e. the discharge limit of 40 ppm was well fulfilled. This was obtained without any use of produced water chemicals.
- The hydrocyclones for treatment of produced water from the 1st stage separator (via the flocculation vessel), had a very good separation efficiency of 92 - 95% at normal operation (i.e. Hydroflok was operated without chemical injection).
- An increased hydrocyclone efficiency of 96 - 97% was observed in the tests with flocculant injection (5, 10 and 20 ppm WT-34). At the same time, a reduced discharge of hydrocarbons in the produced water overboard was observed, from 20 - 23 ppm at normal operation to 10 - 13 ppm with flocculant injection. Also, the water samples were visually cleaner with flocculant injection.
- At the present water production, the flocculation vessel operates as a 1-g separator upstream the hydrocyclones as oil is skimmed off from the vessel. 1-g separation is

possible due to larger oil droplets than expected at the inlet of the vessel (d_{v50} approx. $12 \mu\text{m}$) together with high oil concentration thereby high coalescence in the vessel.

The conclusion is that at the present low water production of about 50% of design, the turbulence and retention time provided by the flocculation vessel alone promotes small oil droplet coalescence sufficient for improved oil separation without addition of produced water chemicals.

After approx. 3 years of operation, new wells were brought on stream June 1998 giving tougher emulsions thereby more difficult produced water to treat. The total water production was about $25,000 \text{ m}^3/\text{d}$ (157 k Bbl/d) corresponding to 63% of the total design flow. The concentration of hydrocarbons in the produced water from the 1st stage separator was 500 - 1,500 ppm. Injection of 2 ppm of produced water chemical upstream the flocculation vessel was required to achieve 20 - 25 ppm oil in the water discharge to sea.

The benefits which the Hydroflok system brings to the Troll B produced water system are:

- Cost savings in the form of eliminated produced water chemical injection during the first 2.5 years of operation
- Ability to handle worse quality produced water from increased water cut and tougher emulsions, by injecting a small amount of chemicals and still achieving 20 - 25 ppm oil in the produced water discharge to sea.

Troll C, Norsk Hydro. Troll C is the first project where Hydroflok was included in the process design from the concept phase. An extremely difficult produced water was anticipated due to known field characteristics in combination with long transport distances from the sub sea wells. A careful study resulted in the design shown below, including the Hydroflok process upstream the HP hydrocyclones and treatment of LP produced water, hydrocyclone rejects, and degasser skimmings by centrifuges. Troll C is to go on stream in 1999/2000.

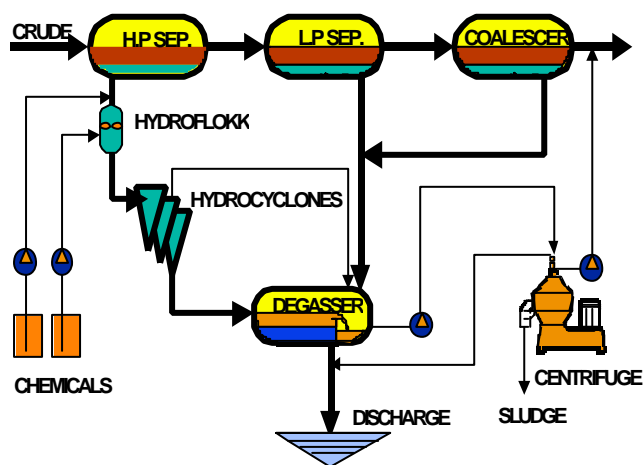


Fig. 11 Troll C process diagram

Yme Field, Statoil. At the Yme field, problems with meeting the discharge limit for produced water was experienced. A mapping of the system was carried out during the fall of 1997 showing extremely small and stable oil droplets in the produced water leaving the separators. Several methods to improve the water quality were discussed, including the Hydroflok process. By this time, the Hydroflok test unit had been designed and built to allow field tests in small scale. The unit was brought out to the Yme field and an optimization test run was conducted. The results obtained are shown in the below figure, given as the hydrocyclone efficiency at different dosing rate (x-axis) and different agitator speed (columns):

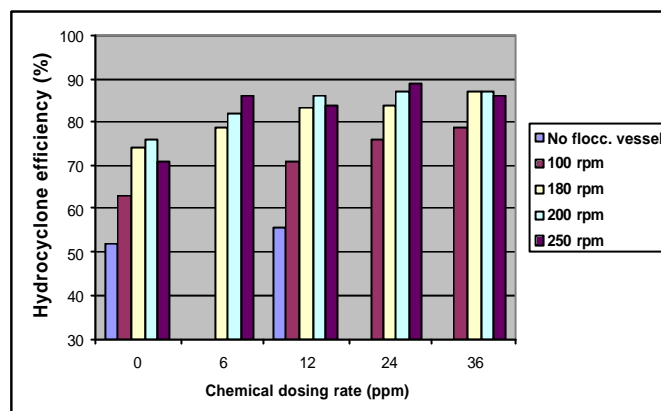


Fig. 12 Results from Hydroflok testing, Yme field

The results show that an improvement is made even without the use of chemicals (chemical dosing rate = 0 ppm), with increased hydrocyclone separation efficiency from 52% without the flocculation vessel to above 70% when including the vessel with agitation. Substantial improvement was made with the addition of the right chemical, the right agitation and the right retention time. The hydrocyclone efficiency increased to 89%. With a hydrocarbon concentration of about 150 ppm in the produced water leaving the 1st stage separator, this was reduced to below 20 ppm in the outlet of the hydrocyclone.

North Sea UK Sector. At this field, produced water from all the three-phase separators (three 1st stage separators together with the 2nd stage separator and the coalescer) is treated in dedicated hydrocyclones. The water discharge lines from the hydrocyclones are commingled prior to entering the produced water flash drum. The hydrocyclone rejects are recirculated to the main process. The existing separation equipment is unlikely to achieve the statutory oil in water limit of 40 ppm consistently. The operator is committed to improving oil in water levels overboard and have internal guidelines such that the concentration of oil should not exceed 20 ppm.

Several methods to improve the produced water quality were discussed, including the Hydroflok process. During fall 1998, the Hydroflok test unit was brought out to the field and a chemical screening program was conducted followed by an

optimization test run. Results from the baseline measurements and the optimization tests for two of the 1st stage separators are summarized in the below figure:

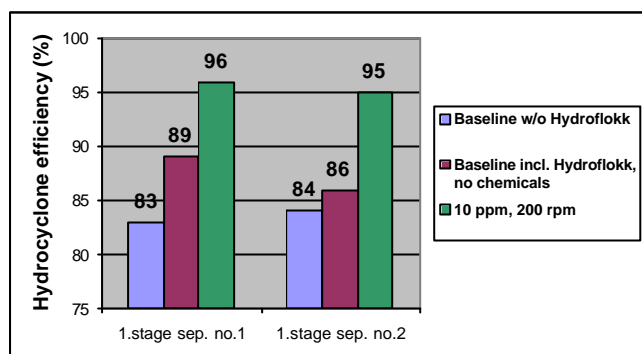


Fig. 13 Results from Hydroflok testing, UK sector.

The following may be highlighted:

- The baseline test results without Hydroflok are in general very good. This is explained by the favorable conditions for the produced water leaving the separators in terms of high pressure of 20 bar(g) and volumetric average oil droplet size of 13 – 15 μm .
- Comparing the results obtained during baseline tests with and without Hydroflok, a somewhat positive effect of the flocculation vessel is shown, especially when testing on produced water from the separator no.1, increasing the hydrocyclone efficiency from 83 up to 89%. The positive effect of retention time and turbulence provided by the flocculation vessel is more clearly seen from results obtained during tests with and without the flocculation vessel together with chemical injection of 10 ppm on produced water from separator no.2. An increased hydrocyclone separation efficiency from 87 up to 95% was obtained when including the vessel (results not shown in the figure).
- Injecting the best working chemical at optimum conditions, identified to be a dosing rate of 10 ppm and an agitator speed of 200 rpm, the hydrocyclone separation efficiency was increased to 95 – 96%. The corresponding oil in water concentrations at the inlet / outlet of the hydrocyclones were 200 / 8 ppm and 1170 / 65 ppm for water from separator no.1 and separator no.2 respectively.

Conclusions

Based on proven technology, Hydroflok is a specially developed process for the flocculation of oil droplets in produced water. Features of the Hydroflok system include vigorous, optimized agitation and retention time together with the use of specially selected chemicals. The flocs formed are stable and strong and of the correct size for efficient removal in the subsequent separation stage, which typically includes

hydrocyclones. The Hydroflok installation at the Troll B platform has proven very successful and resulted in cost savings in the form of eliminated produced water chemicals during the first 2.5 years of operation together with the ability to handle worse quality produced water. The Hydroflok system has also successfully been tested at several offshore platforms showing its ability to flocculate small oil droplets thereby increasing the hydrocyclone separation efficiency.

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