Less Oil In, Less Oil Out: A Holistic Approach to Enhanced Produced Water Treatment

Dr. Alastair Sinker
Business Development Manager,
Cyclotech Ltd

Recent demands from legislation and operators have meant that offshore platforms are now looking to further reduce their oil discharges to sea. Cyclotech suggests a holistic approach to the problem, where each stage of the treatment process is enhanced by the application of new space efficient technology to standard equipment. Proposed solutions include the innovative use of an ultrasonic coalescer in the production separator, a fibre coalescer in the deoiling hydrocyclone vessel and a compact flotation unit for tertiary treatment.

1 INTRODUCTION

The typical European offshore produced water treatment system has generally consisted of a dedicated deoiling hydrocyclone system treating the separated water stream from each three-phase production separator. The treated water from the hydrocyclones is then co-mingled and routed to a common degassing vessel fitted with an oil skimming facility, which may also have the option for gas to be to sparged or induced into it (see Fig. 1).

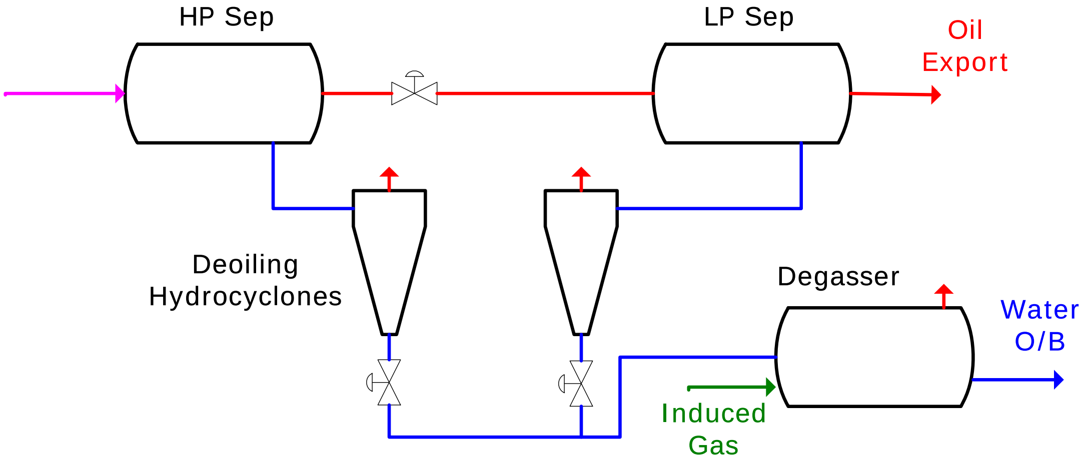


Figure 1 - Typical produced water treatment system

All these components are mechanical separators and primarily rely on the density difference between the oil and water phase to achieve separation. However, there are many of these systems in operation that do not achieve their design outlet water qualities. The most common reasons for this are:

1. **Small inlet drop size distributions** – caused by dispersion sensitivity to high shear intensity regions of the process such as valves and pumps – mechanical separation performance is very sensitive to inlet drop size distribution.

2. **Adverse interfacial chemistry** – caused by changes in reservoir chemistry but more commonly by an increasing "cocktail" of chemicals commonly added to a modern oil and gas production process e.g. scale inhibitors, corrosion inhibitors, well treatment fluids, demulsifiers, and platform drain fluids containing a host of different detergents, solvents and colloidal particles. These can complicate the emulsion interfacial chemistry to resist coalescence mechanisms while lowering the interfacial tension to increase sensitivity to droplet break up processes.
3. **Adverse physical properties of phases** - high viscosities, low phase density difference.
4. **Long-term changes in field conditions** e.g. decreasing temperature and/or pressure. Mechanical separation performance is highly sensitive to operating temperature and decreasing operating pressures can reduce hydrocyclone turndown and separation performance**.**
5. **Sub optimal process designs** e.g. production separators fitted with poorly designed internals, poor hydrocyclone liner geometries, poor IGF vessel design.

Traditional produced water treatment systems were originally conceived to process water effluent discharged from the production separator(s) to ensure that the overboard discharge limit of 40 mg/l, generally required by environmental legislation, was achieved. This has recently been driven down to 30 mg/l in the North Sea (monthly average from 01/01/2006, OSPAR) and, with environmental stewardship now becoming a key reporting area for the major operating companies, much lower stretch targets (potentially down to 15 - 20 mg/l) are often self-imposed. Given that many platforms were struggling to meet the 40 mg/l limits, these new demands are clearly onerous for many facilities.

Improvements in water quality can be obtained by fine-tuning the process, for example optimising the producing well profile; the separator liquid levels and the hydrocyclone pressure drop characteristics. However, in most circumstances, these types of process "tweaks" do not usually result in a substantial improvement in produced water quality and thus other conventional solutions are generally investigated. These include:

- Injection of a water clarifier chemical.
- Implementation of a produced water reinjection scheme.
- Upgrading separator hardware.
- Installation of a final bolt on tertiary treatment equipment e.g. centrifuges, IGFs, TPIs, filter/coalescers, oil absorbtion cartridge filters, walnut shell filters etc.

The most common of these methods is chemical injection as modern water clarifiers can be highly effective, even at very low injected dosages. However, the majority of these tend to be highly toxic Class A or B chemicals that tend to partition into the aqueous phase and, hence, are discharged to the environment with the produced water. Water clarifiers also add a considerable operating expense since the chemicals are expensive, the injection systems require regular operator attention and dosage and chemical type need constant optimisation through field life.

Produced water re-injection eliminates the overboard disposal problem but represents a significant capital investment and raises new operational concerns, like maintaining disposal well injectivity and pump availability.

Investment in separator hardware can have benefits but tends to be focussed downstream of the main production separators, perhaps by replacing an ageing hydrocyclone system with a more modern variant or retrofitting the degassing vessel with IGF internals. However, in many cases, the water quality problem is addressed by simply bolting on a tertiary treatment system, such as a oil absorption or coalescer cartridge systems or a Wallnut Shell filter system to the end of the process. Field experience has suggested that these solutions has had mixed results and while in some cases, the water discharge quality targets have been met, there can still be high consumable costs (regular replacement of cartridges due to high sand and/or oil content), high maintenance requirement (replacement of Cartridges) and can be very space inefficient.

A common problem is that these tertiary treatment systems are seen as an easy fix to produced water treatment problems as they can be simply bolted to the end of an existing process and will provide the required discharge water quality irrespective of the performance of the existing upstream produced water treatment system. As the produced water becomes cleaner, it becomes increasingly more difficult and expensive to further reduce the oil content in the water. It is a fact for every current produced water treatment technology that the less oil contamination at inlet, the less the residual oil in the water outlet – in other words: less oil in, less oil out. To get the most out of a tertiary treatment technology, (which should be considered as a polishing step), the feed to it should contain as low an oil content as possible.

Cyclotech therefore advocate a more holistic approach to improving the performance of the produced water treatment system by maximising the performance of each element to unload the duty of each sequential downstream element in the process. This is achieved by the application of a range of innovative technologies to each stage of the treatment process to enhance and extent their efficacy both in terms of separation capability and equipment compactness – a vital consideration for any offshore facility, where produced water treatment capacity needs almost inevitably increase with time.

The following sections describe the technology under development or commercially available from Cyclotech to enhance the separation performance of each element in the produced water treatment process, namely the production separator (primary), the Deoiling hydrocyclone (secondary) and the water polishing/degassing step (tertiary).

2 PRIMARY: PRODUCTION SEPARATOR ENHANCEMENT – PECT-U® (ULTRASONIC COALESCER)

2.1 Concept and System Development

Whilst ultrasound-based instrumentation is widely applied in oil and gas production and exploration, very little use has been made of ultrasound as a processing technique for oilfield fluids. The PECT-U® system (**P**erformance **E**nhancing **C**oalescence **T**echnology – Ultrasound) represents the application of such energy as a basis for speeding the resolution of emulsions.

It has been identified that controlled application of ultrasound as a standing wave can act to destabilise emulsions by inducing droplet coalescence such that separator operation could be enhanced. The technique is effective in both oil and water continuous systems making it applicable to both black oil/condensate de-watering and produced water treatment.

By reflecting the energy propagating from ultrasonic transducers back on itself to produce a standing wave in an emulsion, strong and directed acoustic forces are generated which cause dispersed droplets to migrate towards either nodal or antinodal regions in the field, depending on their density relative to the carrying liquid (see Fig.2). This movement generates local regions of high oil concentration which result in enhanced coalescence activity which increases the rate of emulsion resolution.

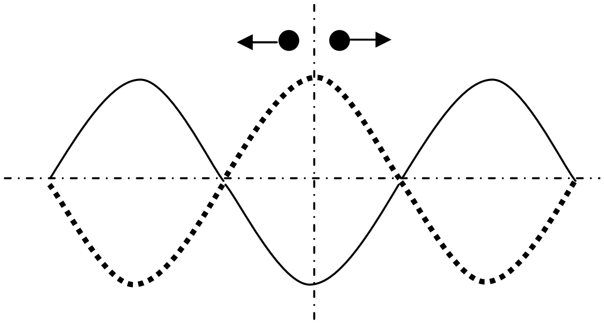


Figure 2 - Standing wave induced droplet movement towards nodal collection zones

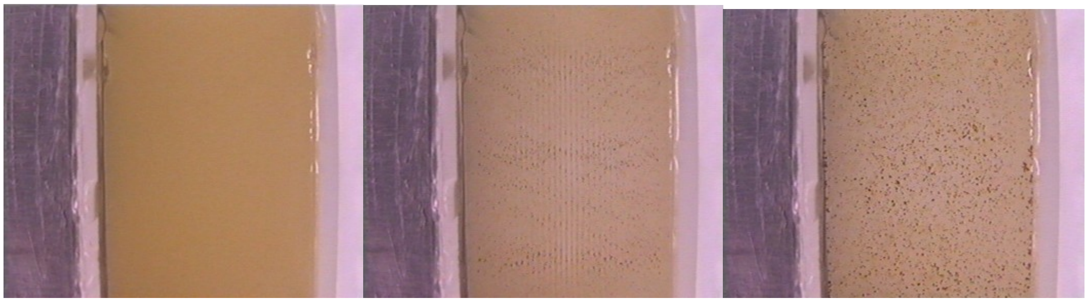
Development of the technique has progressed from lab based batch, bench-top testing with manual frequency control to the use of small scale flow cells in the field with automated frequency tracking, allowing the required resonant conditions to be readily sustained over changing process conditions and extended operational periods. This work has identified that significant coalescence can be achieved within short timescales and the optimal acoustic power and frequency levels required to achieve this. Another key outcome was establishing an understanding of Reynolds number limitations, clarifying that application would be favoured where process velocities are low. It was expected that coalescence rates would tend to fall as continuous phase viscosity increases but it has been noted that this effect is offset in oil continuous emulsions (compared to water continuous systems) by the fact that dispersion concentrations and drop sizes tend to be bigger and the Reynolds Number is lower, which intensifies the influence of the ultrasonic field.

2.2 Performance

A key benefit of this technology is that it works for both water in oil and oil in water emulsions. This is illustrated in the following examples:

2.2.1 Oil in Water Emulsion resolution

Collection and growth in the size of oil droplets from a produced water sample through 5 secs of ultrasonic treatment is illustrated in Fig.3. The 20mm wide cell is viewed from above with the transducer on the LHS: (a) shows the initial untreated sample (vol. median drop size ~ 10μm), (b) reflects the conditions after 5 secs of applying the standing wave, (c) shows oil drops > 1mm floating to the surface a few seconds later after the power had been switched off.



a b c

Figure 3 - Oil droplet coalescence achieved in produced water using ultrasound

2.2.2 Water in Oil Emulsion Resolution

Results from lab testing of a 39 API oil with a finely dispersed water phase (vol. median size ~20µm) are shown in Fig.4. The residence time reflects the treatment time in the standing wave field, with the water cut measured after allowing 1 min sedimentation when the power has been switched off. The lack of water drop out from the untreated reference samples indicates the stability of the emulsion.

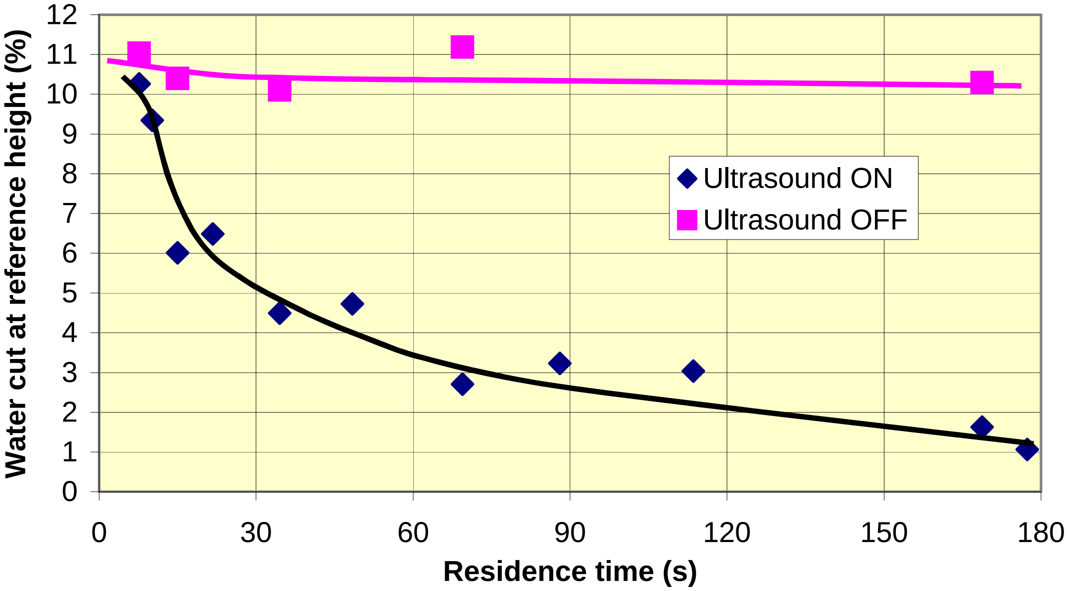


Figure 4 - Improvement in oil emulsion resolution by application of ultrasound

Comparable performance levels have also been found for flowing systems and in the field. However, the freshly generated field emulsions are often easier to coalesce than their lab counterparts, which are artificially manufactured from aged samples with interfacial stability likely to be higher.

2.3 Application

The particular area within the separator where the technology can be most effectively applied is close to the production separator oil/water interface, with particular focus on the dense-packed water droplet layer. Rapid destabilisation of this layer is often the key to minimising carryover of water to the oil stream and carryunder of oil to the water stream. The technology has already demonstrated very effective resolution of a fine solids stabilised layer of this type.

As there is a practical limitation on the maximum diameter of one of these PECT-U® cells, and thus the format of the hardware is a honeycomb-like matrix of flow cell modules operating in parallel across, ~25% of the separator cross-section. This treatment zone may be repeated 2 or 3 times axially down the separator with gaps in between to facilitate gravity separation of the phases.

Currently, the development programme is addressing refinement of the design of this fundamental module (comprising a flow cell, power supply and power control unit), which represents the basic building block for any full-scale system.

2.4 Benefits

The benefits of the ultrasonic coalescer can be summarised as:

- Accelerates interface formation within the separator, potentially eliminating the need for heating and electro-coalescer treatment vessels and minimising the OIW content in the production separator discharge water stream.
- Acts as a catalyst for chemical interactions – reducing demulsifier usage.
- Retrofitable, with no additional vessel space requirement.
- Robust hardware, well established in other industries.
- Delivers separation enhancement to both water and oil pads (unlike electrostatic based coalescers, which can only operate on oil continuous systems).
- Unloads duty of both the produced water treatment and oil processing systems resulting in lower OIW levels to sea and export BS&Ws respectively

3 SECONDARY: DEOILING HYDROCYCLONE ENHANCEMENT – PECT-F® (FIBRE COALESCER)

3.1 Concept

The PECT-F® system (**P**erformance **E**nhancing **C**oalescence **T**echnology – **F**ibre) has been developed to improve the efficiency and extend the operating envelope and flexibility of deoiling hydrocyclone systems while reducing reliance on chemical injection.

The performance of hydrocyclones, as with most separators, is very sensitive to the oil drop size distribution of the produced water stream. In broad terms, a factor of two increase in the drop size would increase the radial settling velocity within the hydrocyclone by a factor of four, significantly raising the likelihood of the droplet reaching the oil core (and therefore being separated).

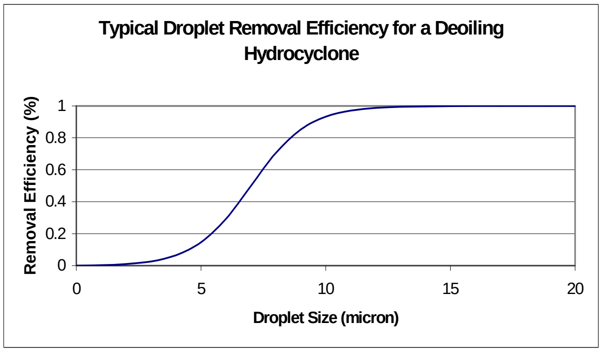


Figure 5 - Typical Deoiling Hydrocyclone cut size curve

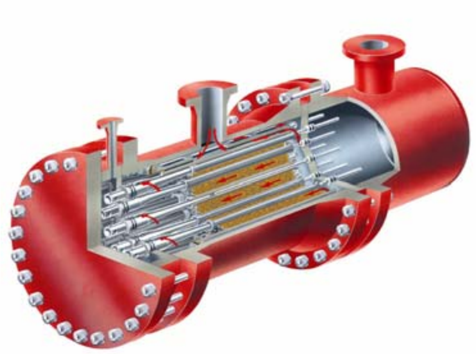


Figure 6 – Conventional Deoiling Hydrocyclone vessel

This effect manifests itself in practice as follows. The graph in Fig. 5 illustrates the typical steep cut size curve for a typical high efficiency deoiling hydrocyclone operating under typical conditions. It can be seen that as the drop size increases from 5μm to 10μm, the separation efficiency will rise dramatically from ~15% to as high as 95% (assuming a mono sized distribution).

With the exception of one or two special cases, the performance of every deoiling hydrocyclone will be governed by the inlet drop size distribution for a given set of physical and operating conditions. This implies that a performance enhancement will be achieved on any system if the inlet drop size distribution is increased. From the above graph, it is clear that only a very moderate increase in the inlet drop size distribution is required to produce a substantial increase in hydrocyclone separation performance. It is this fact that is key to the PECT-F® pre-coalescence technology.

Hydrocyclones have a critical internal geometry to effect their high performance and thus cannot be scaled to suit differing flow capacities. In commercial systems, hydrocyclone liners are manifolded in a vessel fitted with two internal support plates which divide the vessel into three separate chambers – in the case of deoiling hydrocyclones these are oily water inlet, water out and reject oil out. As can be seen from Fig.6, the central inlet chamber of a modern high efficiency system is the largest and has typical residence times of ~10 seconds with flow velocities in the range of 0.05 to 0.2 ms^{-1}. A Reynolds number of ~8,000 implies that the flow field within this chamber is relatively quiescent.

The PECT-F® concept is to fill the inlet chamber with a fibre based coalescing structure. These fibres will entrap the oil droplets as they pass through the media and significantly increase the level of coalescence to produce a coarser oil dispersion (and thus one that is easier to separate) prior to the inlet to the individual hydrocyclone liners. Given the very moderate level of droplet growth required to achieve a substantial improvement in hydrocyclone separation performance, an optimally designed low residence time, high flow velocity and highly open media device is sufficient to produced the required partial pre-coalescence while maintaining a marked insensitivity to solids fouling.

The PECT-F® technology can be fitted into any third party deoiling hydrocyclone vessel; its design is flexible enough to accommodate different liner shapes and sizes and different vessel diameters and configurations.

3.2 Performance

The PECT-F® technology has been tested on over 90 field locations since 1999 and there is currently an installed base of ~50 units. Typical performance improvements in water outlet quality recorded vary from 20% to 80%. Interfacial chemistry will have a significant effect on the overall performance enhancement that the PECT-F® can provide – the more complex the emulsion, the more difficult it is to treat. Experience has shown that the PECT-F® technology works particularly well with condensate emulsions, emulsions which historically Deoiling hydrocyclones have had a poor treatment record with due to their typically very small droplet sizes. However, these emulsions are only kinetically stable by virtue of their small drop size distribution – they are thermodynamically unstable and the condensate droplets will readily coalesce if brought together.

The following case study is a typical example. For an inlet OIW concentration of 500 mg/l, the PECT-F® enhanced hydrocyclone system, without the aid of a deoiler chemical, produced an outlet concentration from the hydrocyclone of ~20 mg/l, compared with ~90 mg/l without PECT-F®, a performance improvement of up to ~85% (see Fig.7).

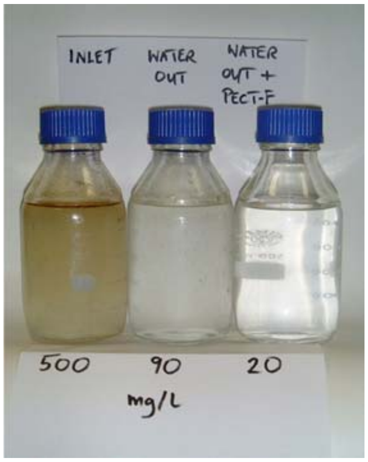


Figure 7 – Typical set of oil-in-water samples

From Fig.8 below, it is clear that the water quality of ~20 mg/l was maintained even at very low operating hydrocyclone pressure drops (0.5 bar inlet to underflow) implying that the turndown of the system had been increased to over 10:1. Operating experience has confirmed this added benefit of extending the operational turndown of the hydrocyclone system by reducing the minimum pressure drop across the unit at which the required water outlet quality is maintained. This is due to the trade off between residence time in the PECT-F® coalescer (the higher the residence time, the greater the level of coalescence, although at very low velocities the lack of turbulent mixing does begin to depress the coalescence rate) and the magnitude of the acceleration field caused by the spinning flow within the hydrocyclone (the higher the spin rate, the better the oil/water separation). At high pressure drops, the residence time in the coalescer is low but the spin rate is high. As the pressure drop declines, the situation reverses thereby maintaining the water quality.

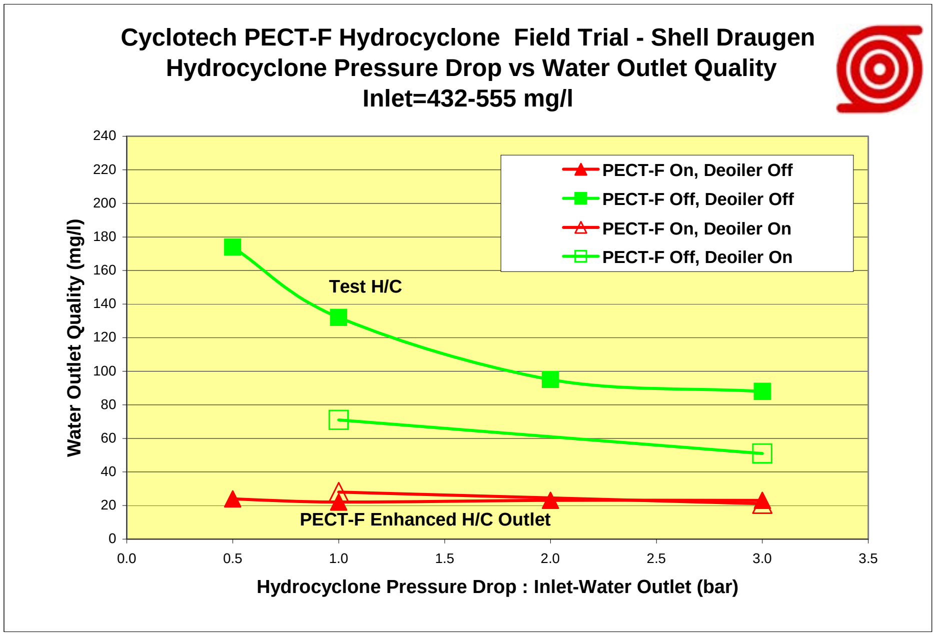


Figure 8 – Hydrocyclone performance with & without deoiler chemical

3.3 Installation

The PECT-F® internals for each hydrocyclone vessel generally constitute a single integrated unit that comprises an outer housing containing a three-stage PECT-F® media system. The PECT-F® housing performs the functions of (1) diverting incoming feed water to the end of the inlet compartment furthest from the liner inlets to maximise contact time in the PECT-F® media and (2) providing a robust housing in which to locate the PECT-F® media.

The PECT-F® housing comprises a cylindrical shroud that fits inside the inlet chamber forming an annular space into which the incoming water must pass. It also provides a means to seal between itself and the inside diameter of the pressure vessel, to prevent the feed water short-circuiting directly from the annulus to the hydrocyclone liner inlet ports. Thus, water entering the vessel must pass down the annulus, away from the hydrocyclone inlets, passing through radial ports in the housing and into the body of the vessel. It must then flow back along the entire length of the inlet chamber of the vessel, through the PECT-F® media, before entering the hydrocyclone liners themselves.

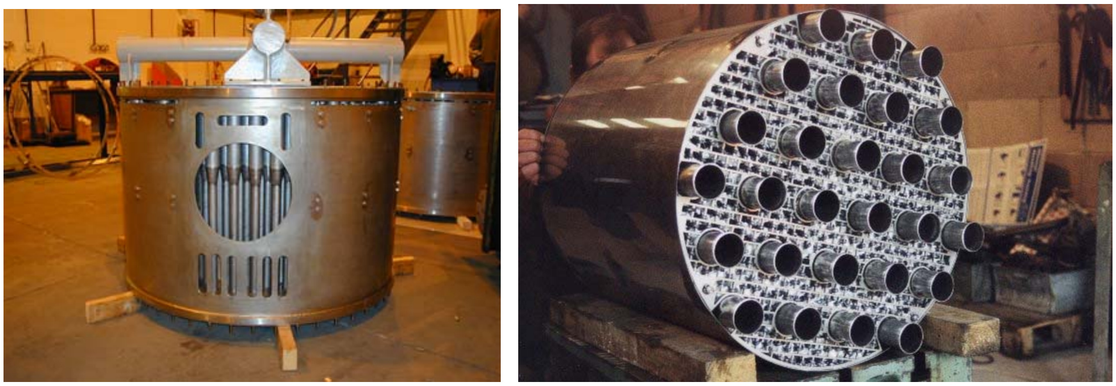


Figure 9 – Full retrofit PECT-F units

The photo on the left of Fig. 9 shows a 44" PECT-F® unit where the liner access tubes can be clearly seen. The photograph on the right shows 24" PECT-F® unit.

The installation of a complete PECT-F® system requires no pipework or vessel modification, no hot work and can be completed in a single shift. Once the PECT-F® system is installed, the liners may be installed /removed at will. This of course also implies that if for whatever reason the system was to fail, the PECT-F® internals could be removed in a single shift to leave the hydrocyclone system in its original state, i.e. with no permanent modifications.

3.4 Benefits

The benefits of the PECT-F® technology can be summarised as follows:

- Enable deoiling hydrocyclone systems, which operate outside the required overboard water discharge limit, to meet specification and potentially stretch targets imposed by operators (perhaps 15 – 20 mg/l).
- Maintain or improve the performance of existing hydrocyclone systems while reducing or eliminating the reliance on chemicals such as water clarifiers.
- Significantly increases the turndown of hydrocyclone systems by maintaining deoiling performance at low hydrocyclone pressure drops.
- The viability of the technology to a particular application can be confirmed relatively quickly and at low cost with a single liner field trial.
- Extend applicability of hydrocyclone-based solutions to both heavy oil and condensate applications where there is a history of poor performance.
- A low capital and operating expenditure solution, when compared to alternatives such as chemical or tertiary treatment based approaches.
- Can be easily retrofitted into existing deoiling hydrocyclone systems *without* the need for any major vessel or pipework modifications.
- Open structure, multi media and surface treated design of coalescing internal ensures optimal performance while being insensitive to solids fouling.
- Pressure drop across coalescer limited to less than 0.5 bar.
- The technology is passive – it requires no control or external power requirement.

4 TERTIARY: DEGASSING VESSEL ENHANCEMENT – DEEPSWEEP™ COMPACT FLOTATION UNIT

4.1 Concept

The philosophy behind the development of the DeepSweep™ Compact Flotation Unit element of the produced water treatment train involves use of a vertically oriented vessel with tangential entry of the process, reducing equipment footprint and enhancing separation with a radial acceleration field. Two processing stages can also be identified within the unit, the first zone providing dissolved gas flotation and the second zone providing induced gas flotation, fed by a pumped partial-recirculation system.

4.2 Design

Features of the design include an inlet format that provides homogenous distribution of incoming oily water into a zone where dissolved gas is released. Gas is induced into the recirculated stream and fine bubbles are generated through use of an innovative adjustable high intensity mixers, which allows optimisation across a range of operating conditions. Droplet/bubble contacting is also established as part of this process. The recirculated water inlet is designed to maximise the region of the DeepSweep™ unit being swept by the inducted bubbles, which are homogeneously distributed.

Figure 10 – DeepSweep™ Compact Flotation Unit

The optimum height/diameter ratio of the unit has been thoroughly developed to finely balance axial flow velocities (which should be minimised for maximum oil separation) with the Swirl characteristics (which should be maximised for maximum oil separation). Similarly, the position of the main process inlet reflects a need to avoid disturbance of the oil pad whilst limiting short-circuiting of oily water to the clean water outlet. The control of axial and radial oil concentration gradients is further enhanced by the swirling flow field and the unique configuration of the internals, maximising the effectiveness of oil and clean water removal. The oil outlet also incorporates a skimming function, minimising water levels in the discharge stream.

Unlike other CFU systems on the market, the DeepSweep™ systems are bespoke designed for each application to ensure full compliance with the requirements of each application. Typical residence times used per stage are between 45 to 90 secs depending on the process characteristics of the application. Where there are particularly onerous water quality requirements or difficult emulsion chemistry to contend with, two-stage systems are used together with provision for flocculant chemical injection at each CFU stage inlet.

4.3 Benefits

These can be summarised as:

- High efficiency - typical outlet concentrations from 5 to 25 mg/l, primarily due to novel adjustable gas induction/mixing device and vessel internals design.
- Small footprint.
- High turndown.
- Scalable bespoke design.
- Suitable for use on floating facilities - low g acceleration field combined with design of oil outlet to allow skimming which is not affected by motion induced slopping (unlike other designs).
- Very low maintenance – gas induction/ mixing done externally to avoid plugging of nozzles etc.
- Insensitive to solids / scale formation – no fine tolerance internals.
- Reduces (or eliminates) the requirement for chemicals.

5 CONCLUSIONS

Recent demands from legislation and operators have meant that offshore platforms are now looking to further reduce their oil discharges to sea. Cyclotech suggest a holistic approach to the problem is adopted, where each stage of the treatment process is enhanced with space efficient equipment, see Fig.11 below rather than putting the majority of the treatment burden on a tertiary treatment stage. The less oil that is fed to any tertiary treatment technology, the greater the water quality achieved from it. In most cases, the equipment availability is also enhanced.

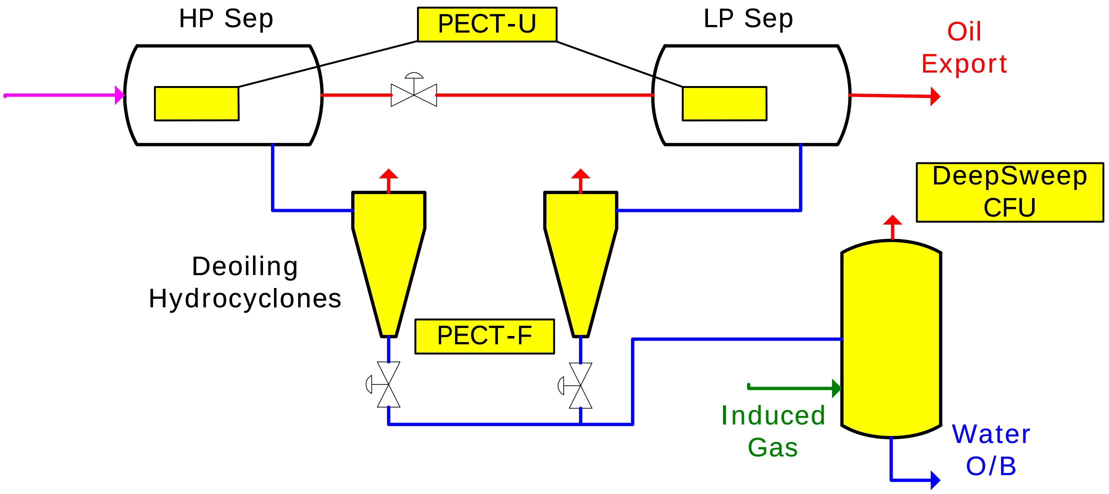


Figure 11 – Enhanced produced water treatment system

At the primary stage, the PECT-U® or ultrasonic coalescer technology is still under development but shows great potential, if sited near the interface in production separators, as a means of increasing phase resolution rates, benefiting oil as well as water stream qualities.

For secondary stage treatment, the PECT-F® or fibre coalescer technology has become established as a viable low cost alternative to the conventional chemical approaches for increasing oil droplet size to get the best performance out of deoiling hydrocyclones. Step changes in discharge concentrations are typical and ease of retrofit directly into the hydrocyclone vessels is a key advantage.

At the tertiary treatment stage, flotation technology has been taken to a new level with the DeepSweep^{TM} Compact Flotation Unit, where vertical orientation and tangential flow entry combine with effective control of gas bubbles to offer an efficient produced water polishing system with a small footprint.